ERDC/ITL TR-01-4

Information Technology Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

Computer-Aided Structural Engineering Project

Investigation of Wall Friction, Surcharge Loads, and Moment Reduction Curves for Anchored Sheet-Pile Walls

William P. Dawkins

September 2001

20011231 092

Computer-Aided Structural Engineering Project

ERDC/ITL TR-01-4
September 2001

Investigation of Wall Friction, Surcharge Loads, and Moment Reduction Curves for Anchored Sheet-Pile Walls

by William P. Dawkins

5818 Benning Drive
Houston, TX 77096

Final report

Approved for public release; distribution is unlimited

Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

Monitored by Information Technology Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Contents

List of Figures

List of Tables

Preface

This report describes three separate studies performed for anchored sheet-pile walls. The first study investigates the effect of the angle of wall/soil friction on bending moments. The second study investigates different procedures for incorporating the influence of surcharge loads on soil pressures. Finally, the third study compares moment reduction curves from several different sources. Funding for the studies and preparation of this report was provided by the Computer-Aided Structural Engineering Program sponsored by Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Civil Works Research and Development Program on Structural Engineering (CWR&D). The work was performed under Civil Works Work Unit 31589, "Computer-Aided Structural Engineering (CASE)," for which Dr. Robert L. Hall, Geotechnical and Structures Laboratory (GSL), U.S. Army Engineer Research and Development Center (ERDC), is Problem Area Leader, and Mr. H. Wayne Jones, Information Technology Laboratory (ITL), ERDC, is the Principal Investigator. The HQUSACE Technical Monitor is Mr. Jerry Foster, CECW-ED.

The investigative studies were performed by Dr. William P. Dawkins, Houston, Texas. Dr. Dawkins also wrote this report.

The work was performed under the general supervision of Mr. H. Wayne Jones, Chief, Computer-Aided Engineering Division (CAED), Information Technology Laboratory (ITL), U.S. Army Engineer Research and Development Center (ERDC), and Mr. Timothy D. Ables, Acting Director, ITL. Mr. Jones is the Project Manager for the CASE project.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and COL John W. Morris III, EN, was Commander and Executive Director.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.03048	meters
foot-pounds	1.355818	joules
kips (force)	4.44822	kilonewtons
kips (force) per square foot	47.880263	kilopascals
kips (mass) per cubic foot	16018.463	kilograms per cubic meter
Pounds (force) per square foot	47.88026	Pascals

1 Introduction

This report contains discussions and results of three separate studies of topics associated with sheet-pile wall design.

Chapter 1 presents an investigation of the effect of the angle of wall/soil friction on bending moments and compares the results of design and/or analysis using classical design procedures or one-dimensional (1-D) soil-structure interaction (SSI).

Chapter 2 discusses the procedures for incorporating the influence of surcharge loads on soil pressures obtained from different pressure calculation methods.

Chapter 3 compares moment reduction curves from several different sources.

Investigation of Effects of Wall Friction on Behavior of Anchored Sheet-Pile Walls

Background

The intent of this study was to investigate the influence of the angle of wall friction on the results of classical design and 1-D SSI analyses of anchored retaining walls.

Data for the system shown in Figure 1 and Table 1, to be considered for this study, were provided by Information Technology Laboratory (ITL). The effects of several permutations of wall friction angle and factors of safety were analyzed using CWALSHT (Dawkins 1991). The results of these analyses are shown in Tables 2, 3, and 4 and are described following Table 4. A table for converting non-SI units of measurement to SI units is presented on page viii.

Explanation of cases

Coulomb coefficients were used for both active and passive pressures for Cases 1 through 3A. Coulomb coefficients were used for active pressures for Cases 4 through 5A. Passive coefficients were obtained from the curves provided in Naval Facilities Engineering Command (NAVFAC) (Headquarters, Department of the Navy 1982) for Cases 4 through 5A.

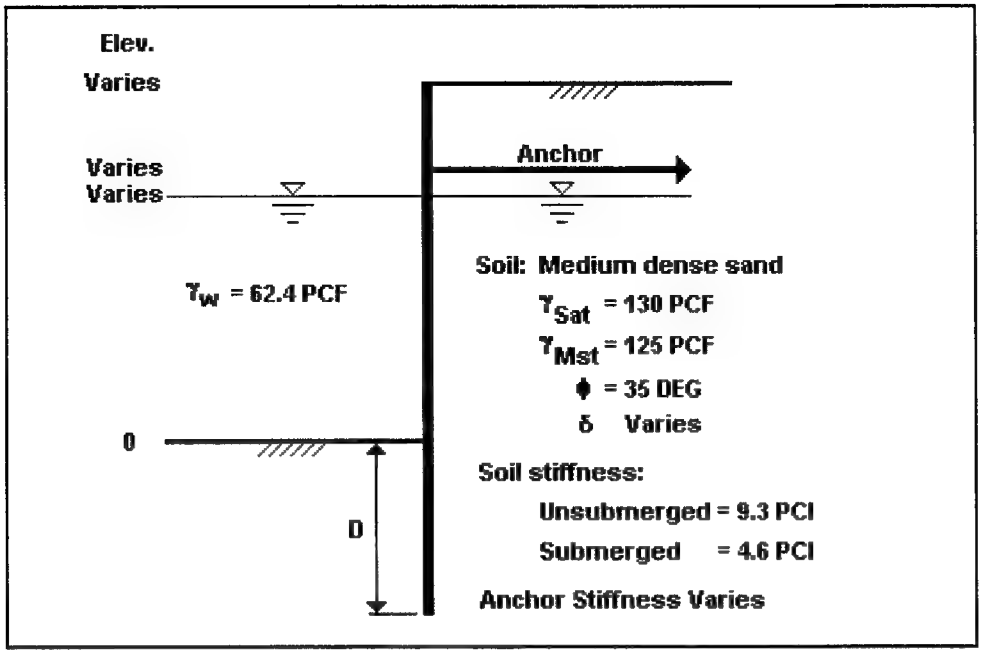

Figure 1. Wall/soil system

Table 1
System Parameters

System	Elevations, ft			
	Wall Top	Anchor	Water	Anchor Stiffness, lb/in.
40-ft Wall	40	31.50	29.00	24×10^3
30-ft Wall	30	23.50	21.75	18×10^3
20-ft Wall	20	15.75	14.50	10×10^3

Table 2
Results of CWALSHT Analyses for 40-ft Wall

Case	Factors of Safety		Wall Friction Angle, deg		Penetration ft	Maximum Moment, lb-ft	Anchor Force lb
	Active	Passive	Rightside	Leftside			
40-1	1	1.5	0	0	17.56	1.574×10^5	1.354×10^4
40-1a	1	1	0	0	13.12	1.345×10^5	1.252×10^4
40-2	1	1.5	8.75 (=ϕ/4)	6.25	14.67	1.321×10^5	1.195×10^4
40-2a	1	1	8.75	8.75	10.19	1.115×10^5	1.099×10^4
40-3	1	1.5	17.59 (=ϕ/2)	12.50	12.40	1.134×10^5	1.070×10^4
40-3a	1	1	17.5	17.50	7.86	9.460×10^4	9.788×10^3
40-4	1	1.5	24.5 (=0.7ϕ)	17.50	11.35	1.030×10^5	9.568×10^3
40-4a	1	1	24.5	24.50	7.10	8.660×10^4	9.112×10^3
40-5	1	1.5	35 (=ϕ)	25.00	10.48	9.194×10^4	9.007×10^3
40-5a	1	1	35	35.00	6.48	7.781×10^4	8.304×10^3

Table 3 Results of CWALSHT Analyses for 30-ft Wall							
Case	Factors of Safety		Wall Friction Angle, deg		Penetration ft	Maximum Moment, lb-ft	Anchor Force lb
	Active	Passive	Rightside	Leftside			
30-1	1	1.5	0	0	13.15	6.590×10^4	7.645×10^3
30-1a	1	1	0	0	9.82	5.630×10^4	7.069×10^3
30-2	1	1.5	8.75 (=ϕ/4)	6.25	10.98	5.529×10^4	6.746×10^4
30-2a	1	1	8.75	8.75	7.63	4.664×10^4	6.205×10^3
30-3	1	1.5	17.59 (=ϕ/2)	12.50	9.28	4.475×10^4	6.041×10^3
30-3a	1	1	17.5	17.50	5.89	3.957×10^4	5.529×10^3
30-4	1	1.5	24.5 (=0.7ϕ)	17.50	8.50	4.312×10^4	5.602×10^3
30-4a	1	1	24.5	24.50	5.32	3.662×10^4	5.148×10^3
30-5	1	1.5	35 (=ϕ)	25.00	7.84	3.847×10^4	$5.087\ 10^3$
30-5a	1	1	35	35.00	4.85	3.254×10^4	4.692×10^3

Table 4 Results of CWALSHT Analyses for 20-ft Wall							
Case	Factors of Safety		Wall Friction Angle, deg		Penetration ft	Maximum Moment, lb-ft	Anchor Force lb
	Active	Passive	Rightside	Leftside			
20-1	1	1.5	0	0	8.78	1.968×10^4	3.386×10^3
20-1A	1	1	0	0	6.56	1.682×10^4	3.130×10^3
20-2	1	1.5	8.75 (=ϕ/4)	6.25	7.33	1.651×10^4	2.988×10^3
20-2A	1	1	8.75	8.75	5.09	1.394×10^4	2.747×10^3
20-3	1	1.5	17.59 (=ϕ/2)	12.50	6.20	1.417×10^4	2.675×10^3
20-3A	1	1	17.5	17.50	3.93	1.182×10^4	2.447×10^3
20-4	1	1.5	24.5 (=0.7ϕ)	17.50	5.68	1.288×10^4	2.480×10^3
20-4A	1	1	24.5	24.50	3.55	1.082×10^4	2.278×10^3
20-5	1	1.5	35 (=ϕ)	25.00	5.24	1.149×10^4	2.252×10^3
20-5A	1	1	35	35.00	3.24	9.727×10^3	2.076×10^3

According to EM 1110-2-2504 (HQDOA 1994), Cases 1,2,3,4, or 5 would be used to determine the design penetration and anchor force for this system, while the "A" variations of these cases would be used to evaluate the design bending moment.

Selection of Sheet-Pile Sections

Following the recommendations of EM 1110-2-2504 (HQDOA 1994), Cases 1A, 2A, 3A, 4A, and 5A were used to select an appropriate steel sheet pile section from the default sections contained in CWALSHT. The selection was based on an assumed modulus of elasticity of 29×10^6 psi, assumed allowable bending stress of 25 ksi, with the design bending moment obtained from the classical design maximum moment reduced according to the NAVFAC values for Rowe's Moment Reduction (Headquarters, Department of the Navy 1982; Rowe 1952; Bowles 1977). The results are shown in Tables 5, 6, and 7.

Table 5 Selection of Sheet-Pile Sections for 40-ft Wall							
Case	Sheet Pile			ρ= $(H+D)^4/Ei$ in.^{2}/lb	Moment Reduction Coefficient	Design Bending Moment, lb-ft	Maximum Bending Stress, Ksi
	Section	Moment of Inertia in.^{4}/ft	Section Modulus in.^{3}/ft				
40-1a	Pz32	220.4	38.3	25.8	0.54	7.26×10^4	22.9
40-2a	Pz27	184.2	30.2	24.6	0.56	6.24×10^4	24.8
40-3a	Pz27	184.2	30.2	20.4	0.59	5.58×10^4	22.2
40-4a	Pz27	184.2	30.2	19.1	0.61	5.28×10^4	21.0
40-5a	Pz27	184.2	30.2	18.1	0.62	4.82×10^4	19.2

Table 6 Selection of Sheet-Pile Sections for 30-ft Wall							
Case	Sheet Pile			ρ= $(H+D)^4/Ei$ in.^{2}/lb	Moment Reduction Coefficient	Design Bending Moment, lb-ft	Maximum Bending Stress, Ksi
	Section	Moment of Inertia in.^{4}/ft	Section Modulus in.^{3}/ft				
30-1A	PZ27	184.2	30.2	9.79	0.81	4.56×10^4	18.1
30-2A	PZ27	184.2	30.2	7.78	0.91	4.24×10^4	16.8
30-3A	PZ27	184.2	30.2	6.44	1.00	3.96×10^4	15.7
30-4A	PZ27	184.2	30.2	6.04	1.00	3.62×10^4	14.4
30-5A	PZ27	184.2	30.2	5.73	1.00	3.25×10^4	12.9

Table 7 Selection of Sheet Pile Sections for 20-ft Wall							
Case	Sheet Pile			ρ= $(H+D)^4/Ei$ in.^{2}/lb	Moment Reduction Coefficient	Design Bending Moment, lb-ft	Maximum Bending Stress, Ksi
	Section	Moment of Inertia in.^{4}/ft	Section Modulus in.^{3}/ft				
20-1A	PZ22	84.4	18.1	4.22	1.00	1.68×10^4	11.2
20-2A	PZ22	84.4	18.1	3.35	1.00	1.39×10^4	9.2
20-3A	PZ22	84.4	18.1	2.78	1.00	1.18×10^4	7.8
20-4A	PZ22	84.4	18.1	2.61	1.00	1.08×10^4	7.2
20-5A	PZ22	84.4	18.1	2.47	1.00	9.73×10^3	6.5

SSI Analyses

SSI analyses using CWALSSI (Dawkins 1994) were performed for the wall/soil system of Figure 1 with depths of penetration from the classical design Cases 1, 2, 3, 4, and 5 of Tables 2 through 4 and the sheet-pile sections shown in Tables 5 through 7. Unfactored soil (i.e., active and passive factors of safety equal to 1) and wall friction values indicated in the "A" cases of Tables 2 through 4 were used. Both rigid and flexible anchors were considered. The flexible anchor stiffnesses shown in Table 1 were based on a steel rod with cross section area producing an anchor stress of approximately 25 ksi, based on the anchor forces shown in Tables 2 through 4 and an effective length of 50 ft. The results of the SSI analyses are shown in Tables 8, 9, and 10.

Table 8
Results of SSI Analyses for 40-ft Wall

Case	Wall Friction Angle, deg	Wall Bottom Elevation, ft	Maximum Moment, lb-ft	Anchor Force, lb	Maximum Deflection, in.
40-1AR	0	-17.56	1.253×10^5	2.163×10^4	8.2
40-1AF	0	-17.56	1.277×10^5	1.867×10^4	8.7
40-2AR	8.75 (=ϕ/4)	-14.67	1.063×10^5	2.032×10^4	7.7
40-2AF	8.75	-14.67	1.084×10^5	1.740×10^4	8.2
40-3AR	17.5 (=ϕ/2)	-12.40	9.458×10^4	1.859×10^4	6.8
40-3AF	17.5	-12.40	9.673×10^4	1.588×10^4	7.2
40-4AR	24.5 (=0.7ϕ)	-11.35	8.697×10^4	1.746×10^4	6.3
40-4AF	24.5	-11.35	8.903×10^4	1.487×10^4	6.9
40-5AR	35 (=ϕ)	-10.48	7.817×10^4	1.614×10^4	6.7
40-5AF	35	-10.48	8.011×10^4	1.369×10^4	6.1

Table 9
Results of SSI Analyses for 30-ft Wall

Case	Wall Friction Angle, deg	Wall Bottom Elevation, ft	Maximum Moment, lb-ft	Anchor Force, lb	Maximum Deflection, in.
30-1AR	0	-8.78	5.930×10^4	1.077×10^4	3.6
30-1AF	0	-8.78	6.033×10^4	9.083×10^3	3.8
30-2AR	8.75 (=ϕ/4)	-7.33	5.067×10^4	9.780×10^3	3.2
30-2AF	8.75	-7.33	5.169×10^4	8.188×10^3	3.4
30-3AR	17.5 (=ϕ/2)	-6.20	4.381×10^4	9.017×10^3	3.0
30-3AF	17.5	-6.20	4.477×10^4	7.496×10^3	3.2
30-4AR	24.5 (=0.7ϕ)	-5.68	3.981×10^4	8.548×10^3	2.9
30-4AF	24.5	-5.68	4.073×10^4	7.065×10^3	3.0
30-5AR	35 (=ϕ)	-5.24	3.551×10^4	8.009×10^3	2.8
30-5AF	35	-5.24	3.631×10^4	6.565×10^3	2.9

Table 10
Results of SSI Analyses for 20-ft Wall

Case	Wall Friction Angle, deg	Wall Bottom Elevation, ft	Maximum Moment, lb-ft	Anchor Force, lb	Maximum Deflection, in.
20-1AR	0	-8.78	1.886×10^4	4.418×10^3	1.8
20-1AF	0	-8.78	1.920×10^4	3.621×10^3	1.9
20-2AR	8.75 (=ϕ/4)	-7.33	1.587×10^4	4.035×10^3	1.9
20-2AF	8.75	-7.33	1.620×10^4	3.270×10^3	1.9
20-3AR	17.5 (=ϕ/2)	-6.20	1.360×10^4	3.764×10^3	2.0
20-3AF	17.5	-6.20	1.390×10^4	3.006×10^3	1.9
20-4AR	24.5 (=0.7ϕ)	-5.68	1.234×10^4	3.570×10^3	2.0
20-4AF	24.5	-5.68	1.261×10^4	2.842×10^3	1.9
20-5AR	35 (=ϕ)	-5.24	1.100×10^4	3.370×10^3	1.9
20-5AF	35	-5.24	1.123×10^4	2.658×10^3	1.9

Comparison of Results

Results of the SSI analyses and those from the classical "A" cases, together with classical design penetrations, are shown in Figures 2 through 28. The maximum bending moments predicted by the classical Free Earth Method and the two SSI variations are nearly the same. The slight differences in shapes of the moment diagrams are a result of: the higher (passive) pressures above the anchor in the SSI analyses; the location of the resultant of the passive pressure distribution on the left side of the wall below the dredge line; and, the differences in penetration for the classical and SSI systems. Soil pressures below the anchor are full active values in all cases. The pressure distributions for the classical 1A case and the SSI 1AR case are shown in Figures 10, 19, and 28.

Conclusions

The following conclusions are based on the results of this limited study:

a. The relationships between depth of penetration, maximum bending moment, and anchor force with increasing wall friction angle are nearly linear.

b. An initial item of interest was whether the angle of wall friction could be adjusted to produce SSI moments which would more closely approximate the moments resulting from application of Rowe's moment reduction to the classical Free Earth moments. Figure 8 suggests that the desired effect cannot be achieved for very flexible walls. For stiffer walls, Figures 17 and 26, there is little or no reduction permitted, and both Classical and SSI analyses yield essentially the same maximum moments.

c. The anchor force predicted by the classical Free Earth Method is significantly lower than that indicated by the SSI analysis (Figures 9, 18, and 27). Rowe gave reduction factors for anchor forces similar to his moment reduction curves. The effect of application of anchor force reduction factors has not been investigated. However, the results of this study suggest that reduction of the Free Earth anchor force would be unconservative. In all cases, the Free Earth Method significantly underestimates the anchor force as compared to the SSI method.

d. The SSI analysis cannot represent the behavior of the system observed by Rowe. The Winkler model of the nonlinear soil cannot reproduce the conditions (which have been suggested to be the result of soil arching between the anchor and the passive zone below the dredge line) observed in Rowe's experiments.

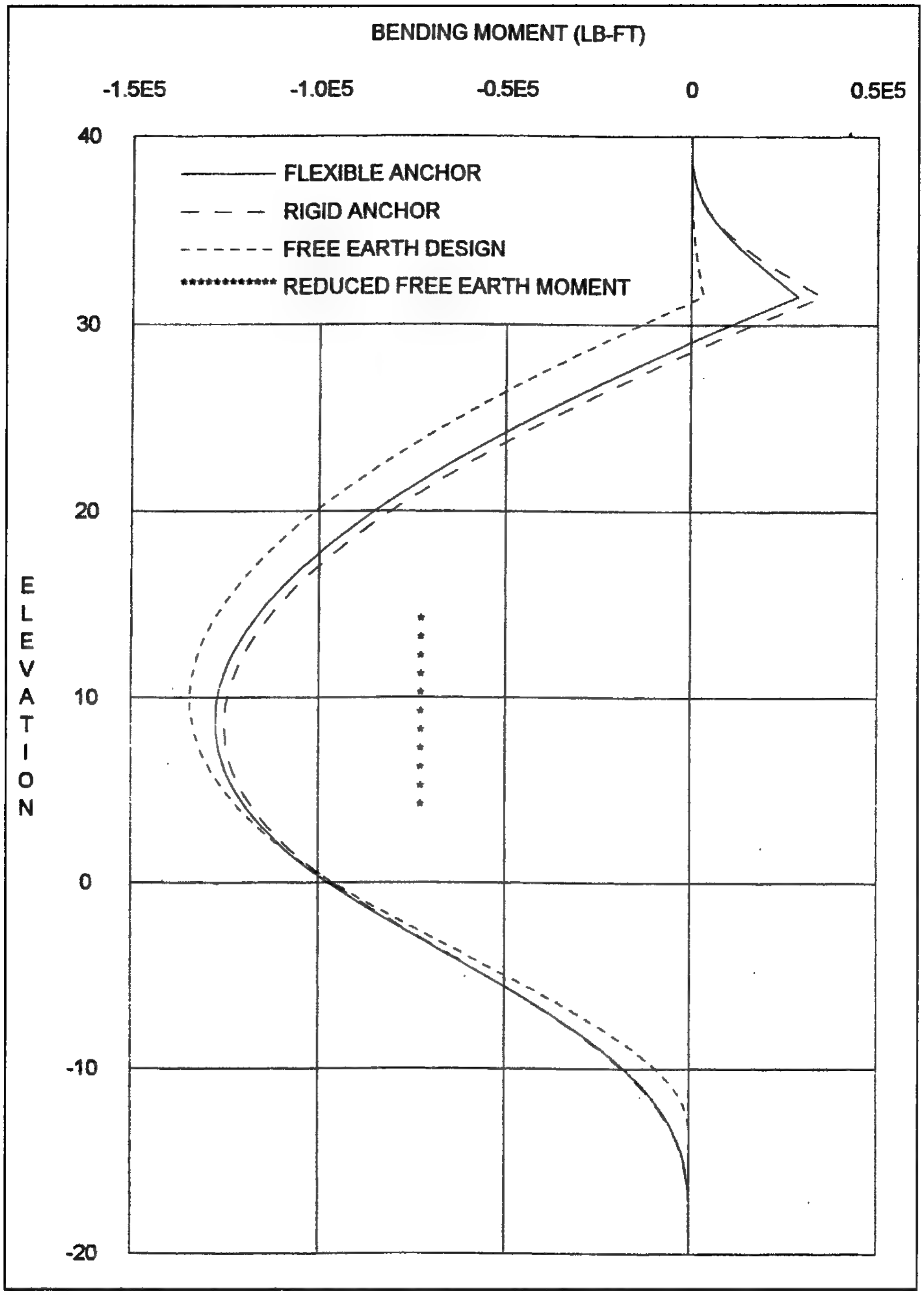

Figure 2. Bending moments for wall friction = 0 for 40-ft wall

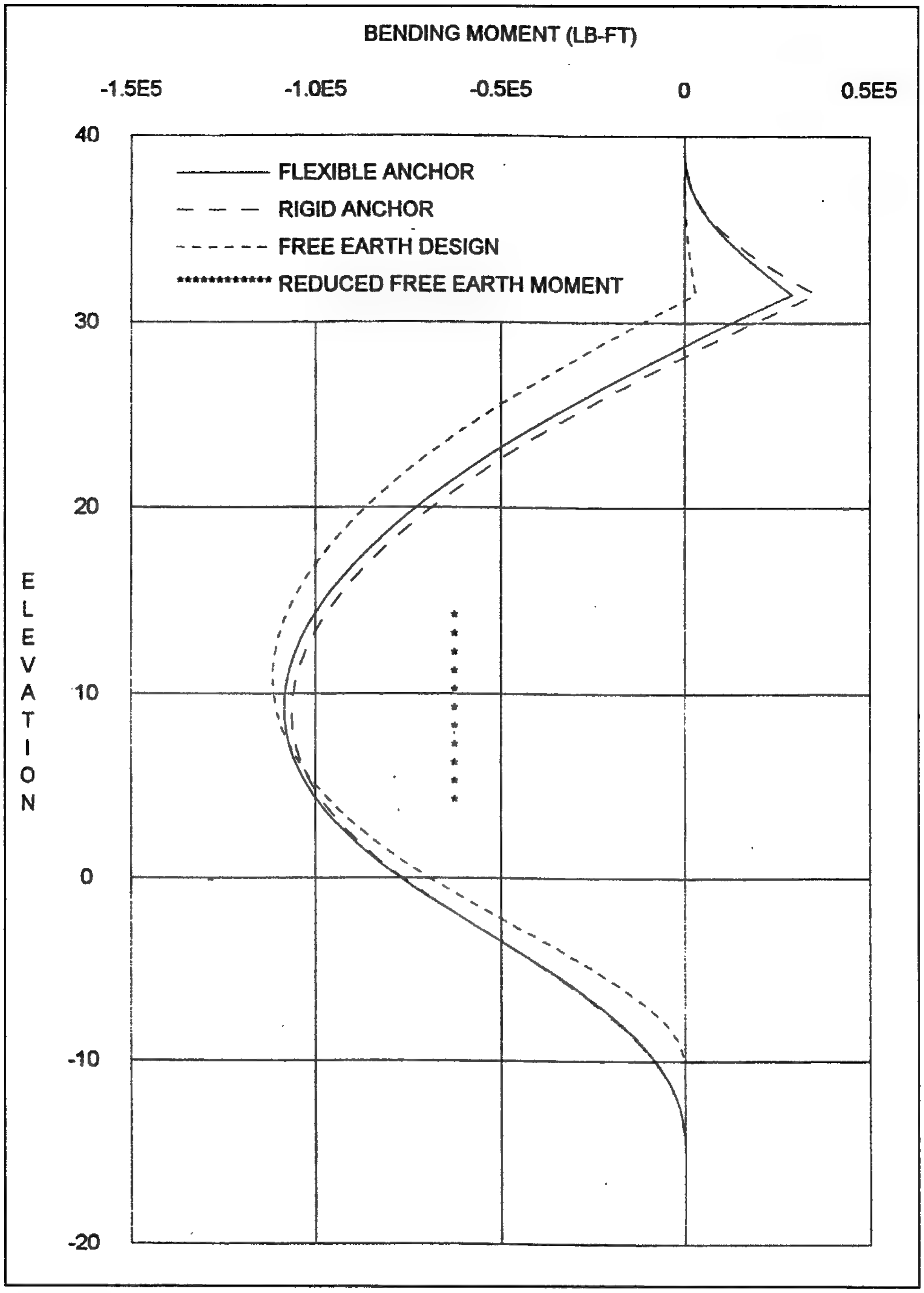

Figure 3. Bending moments for wall friction = PHI/4 for 40-ft wall

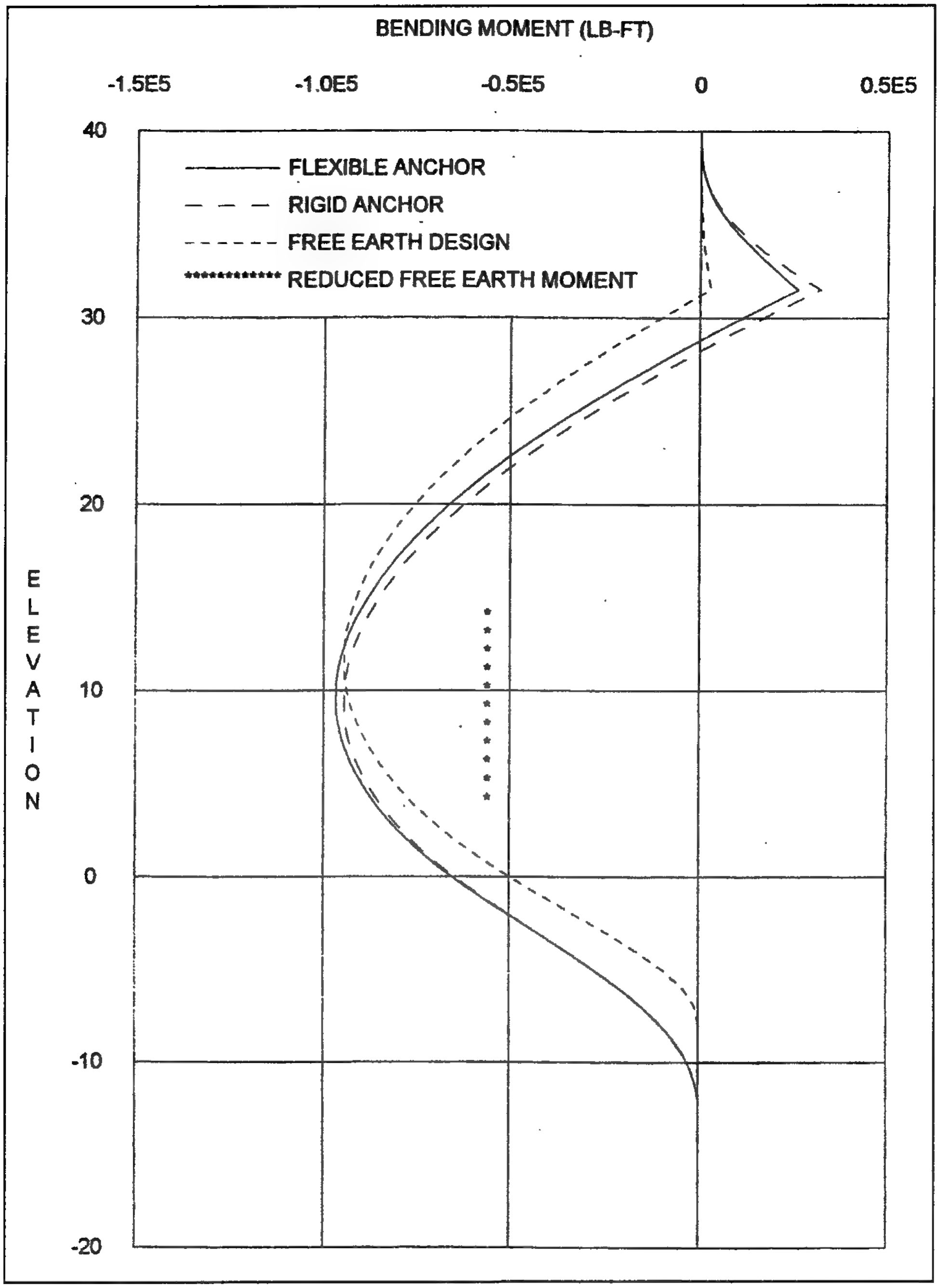

Figure 4. Bending moments for wall friction = PHI/2 for 40-ft wall

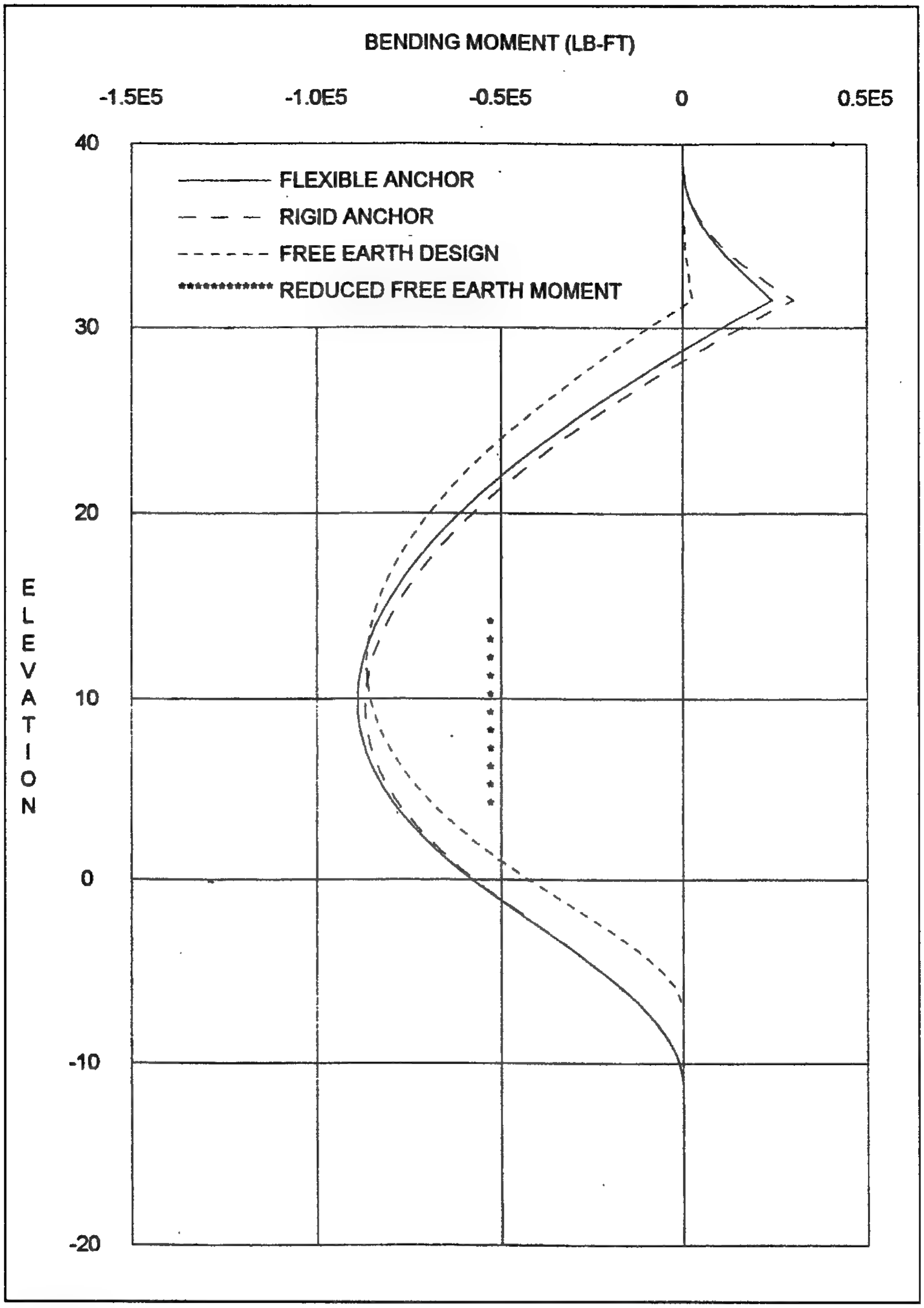

Figure 5. Bending moments for wall friction = 0.7*PHI for 40-ft wall

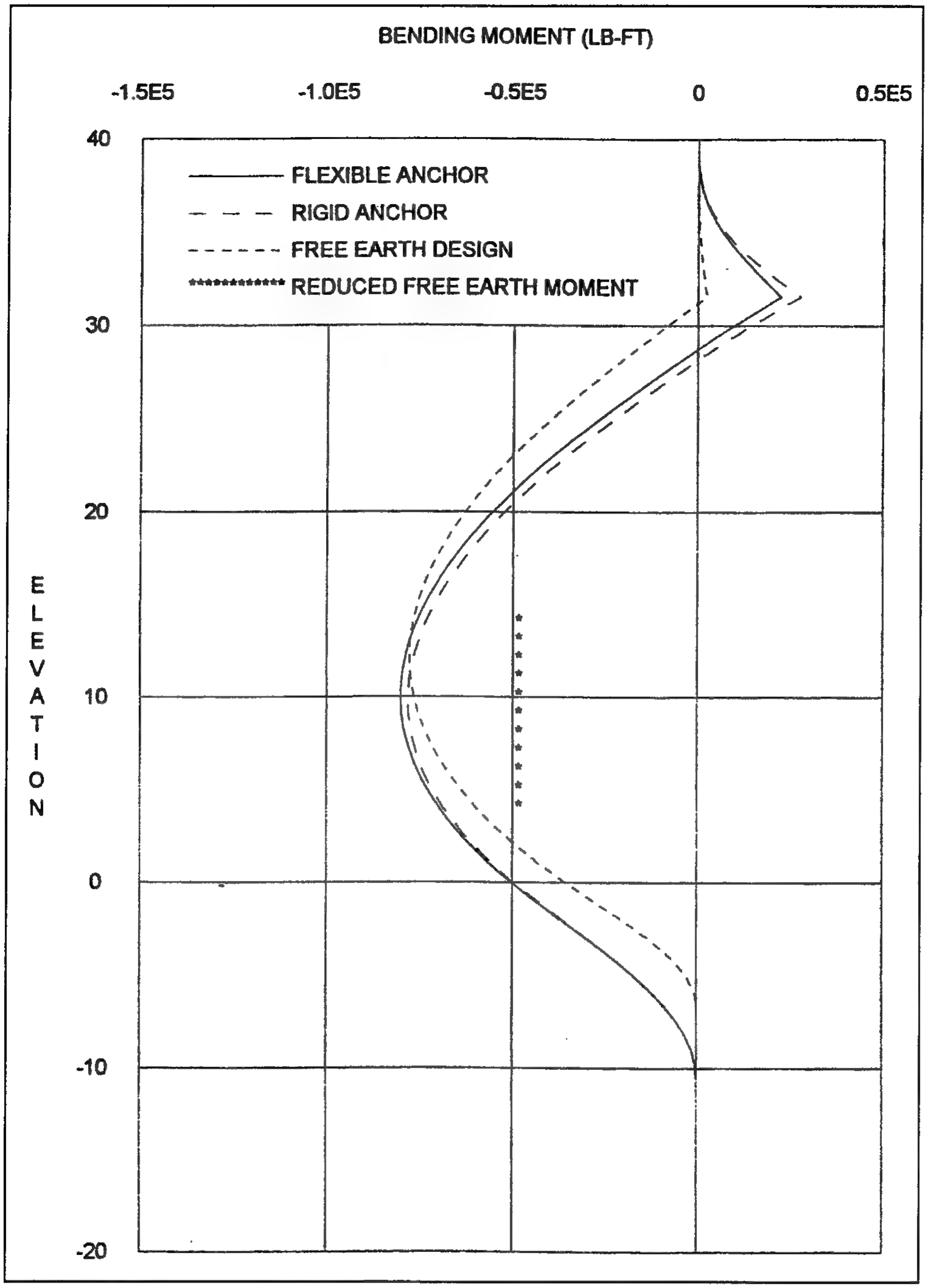

Figure 6. Bending moments for wall friction = PHI for 40-ft wall

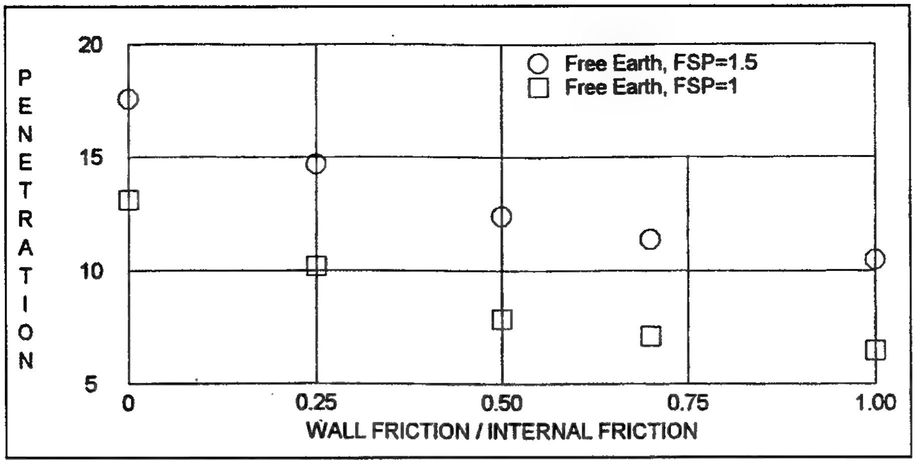

Figure 7. Effect of wall friction on penetration for 40-ft wall

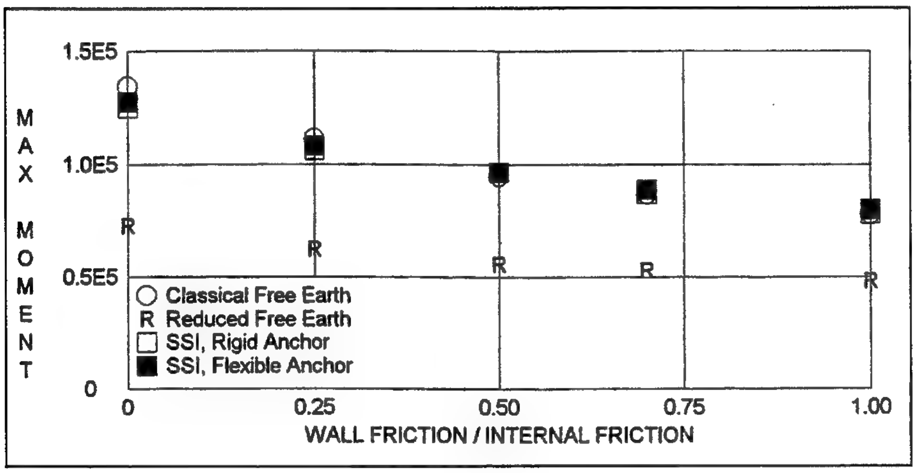

Figure 8. Effect of wall friction on maximum bending moment for 40-ft wall

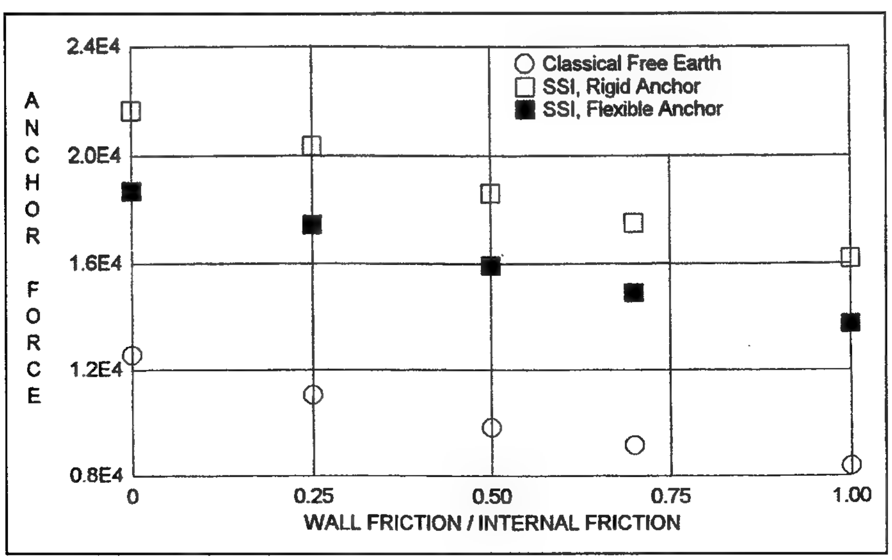

Figure 9. Effect of wall friction on anchor force for 40-ft wall

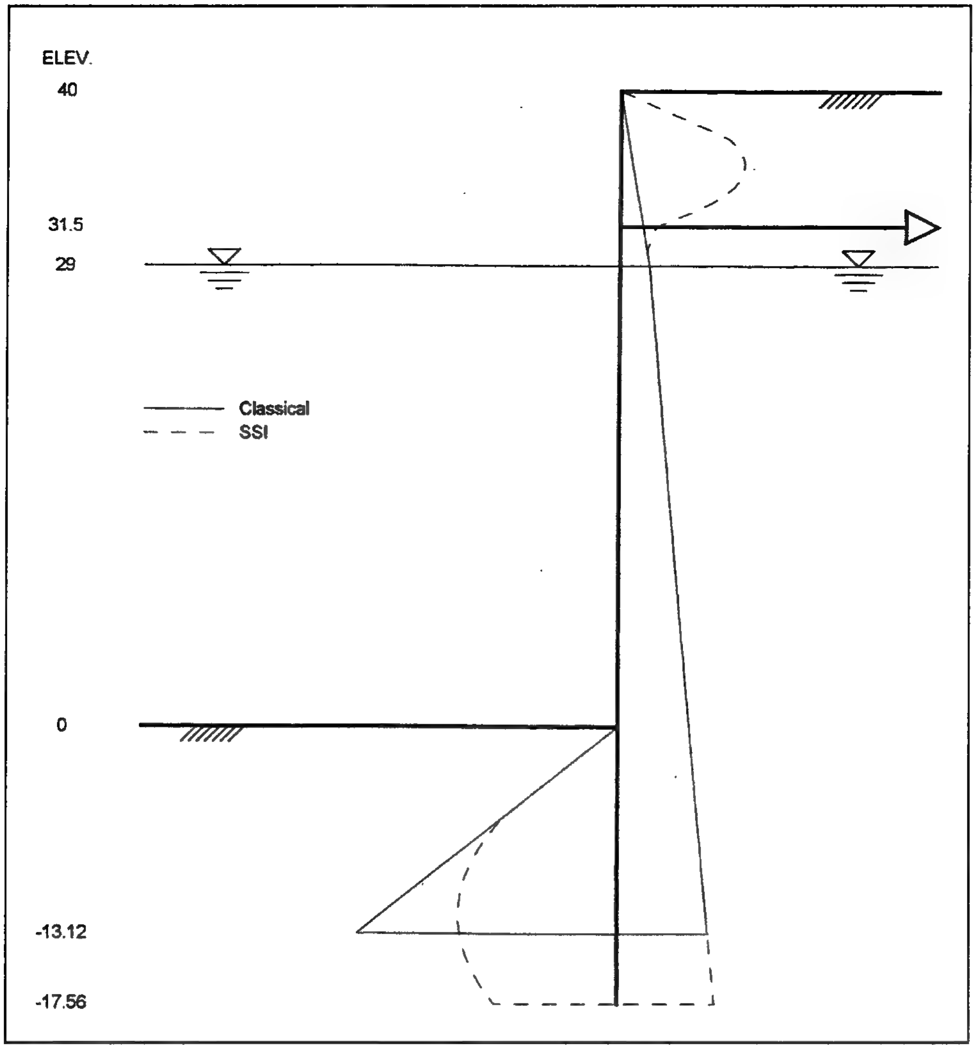

Figure 10. Soil pressures for classical Case 1A and SSI Case 1AR for 40-ft wall

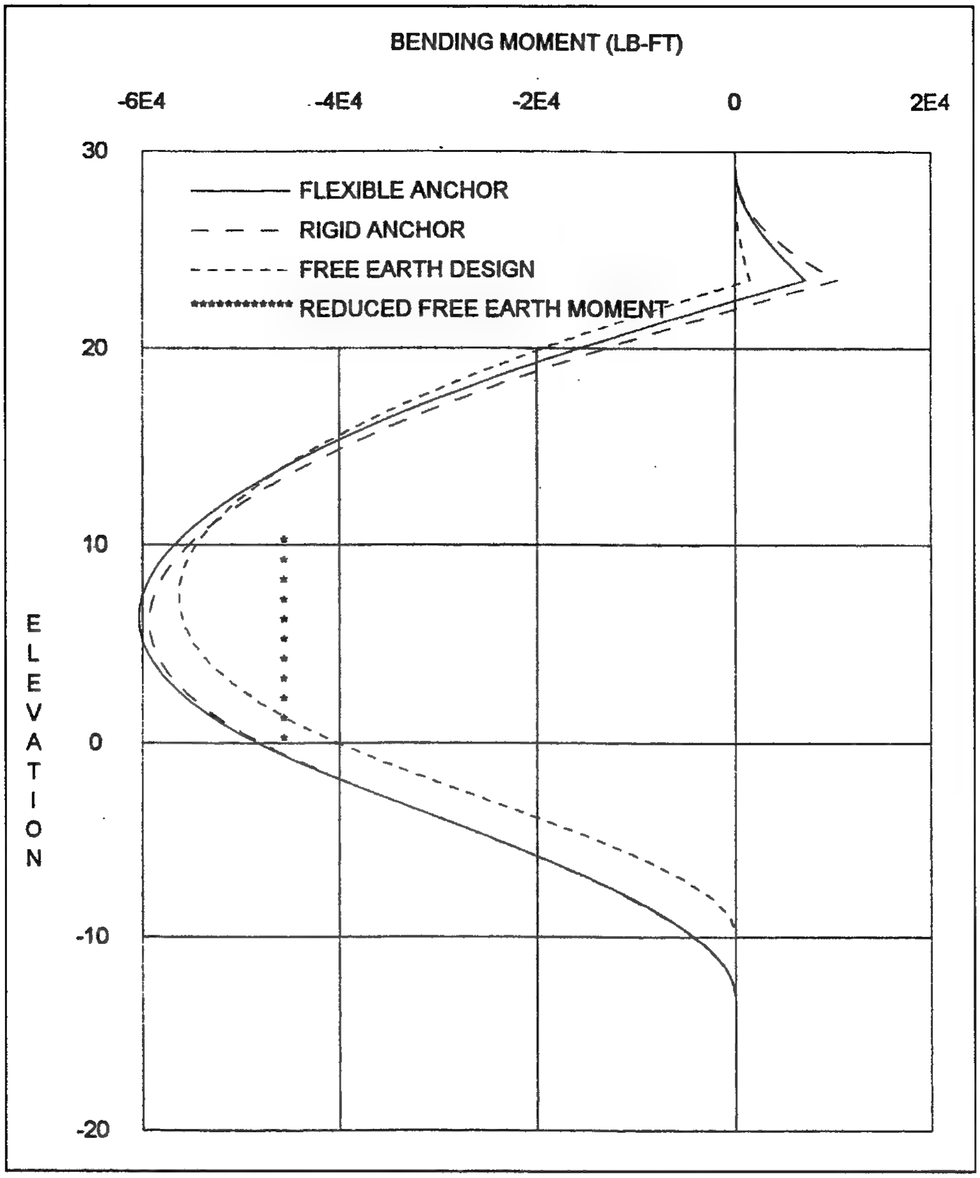

Figure 11. Bending moments for wall friction = 0 for 30-ft wall

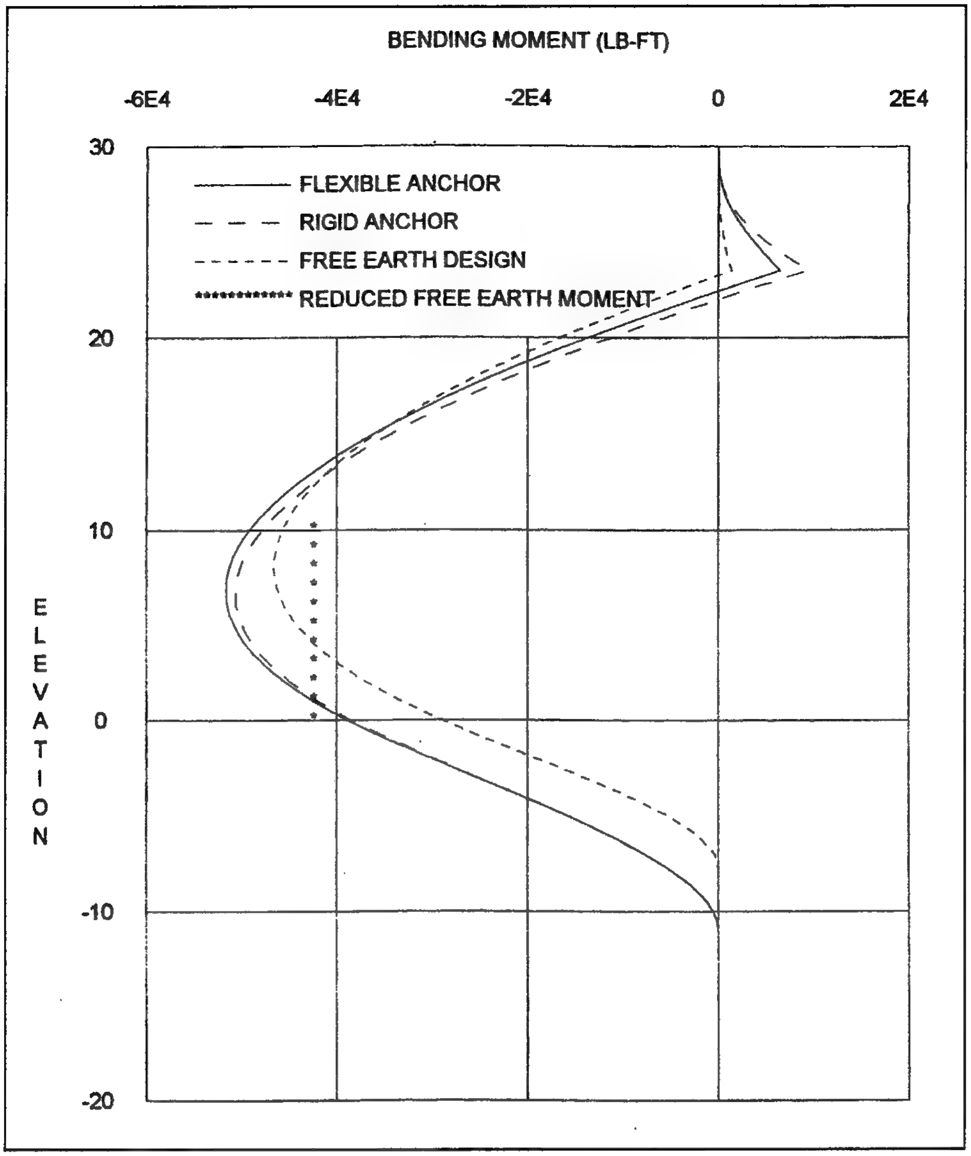

Figure 12. Bending moments for wall friction = PHI/4 for 30-ft wall

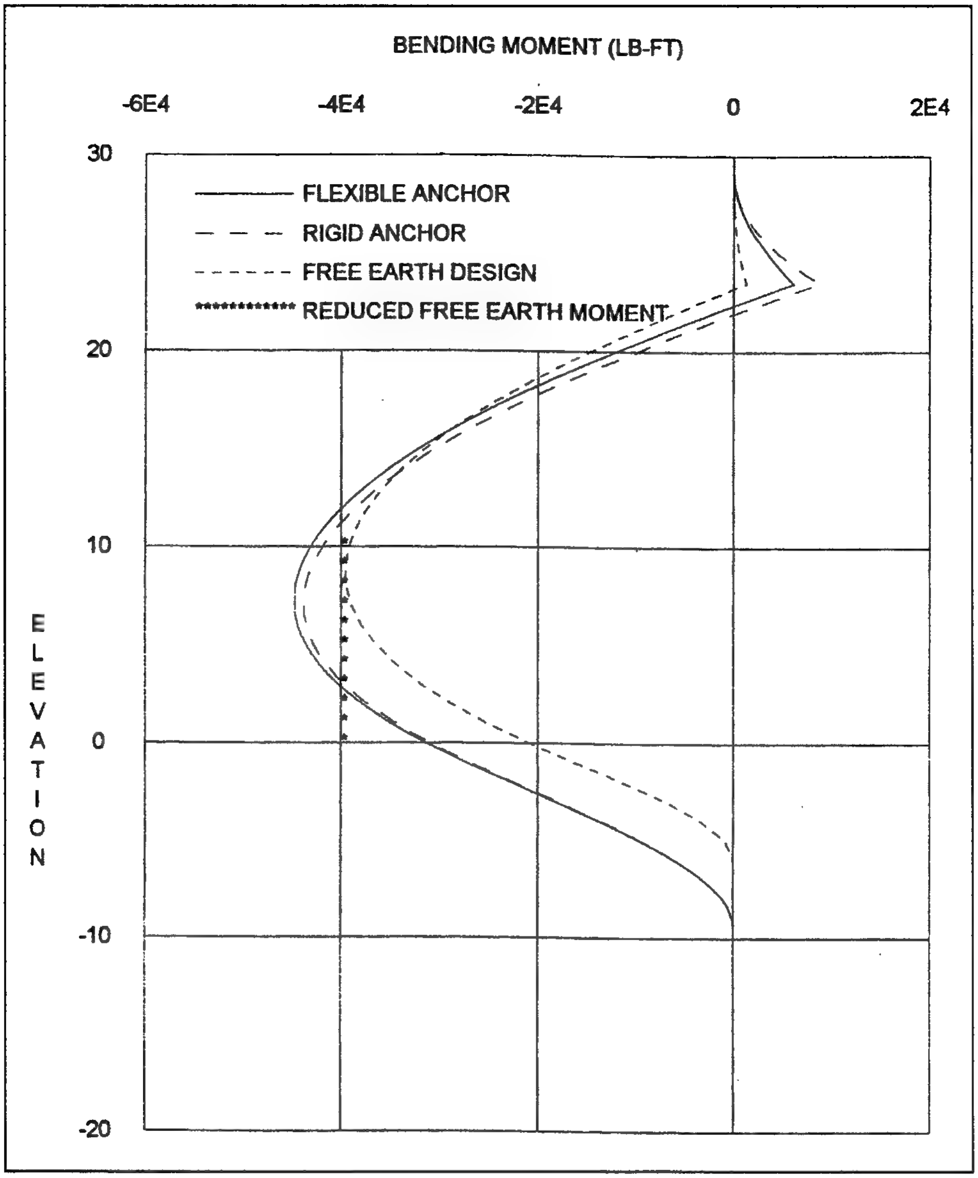

Figure 13. Bending moments for wall friction = PHI/2 for 30-ft wall

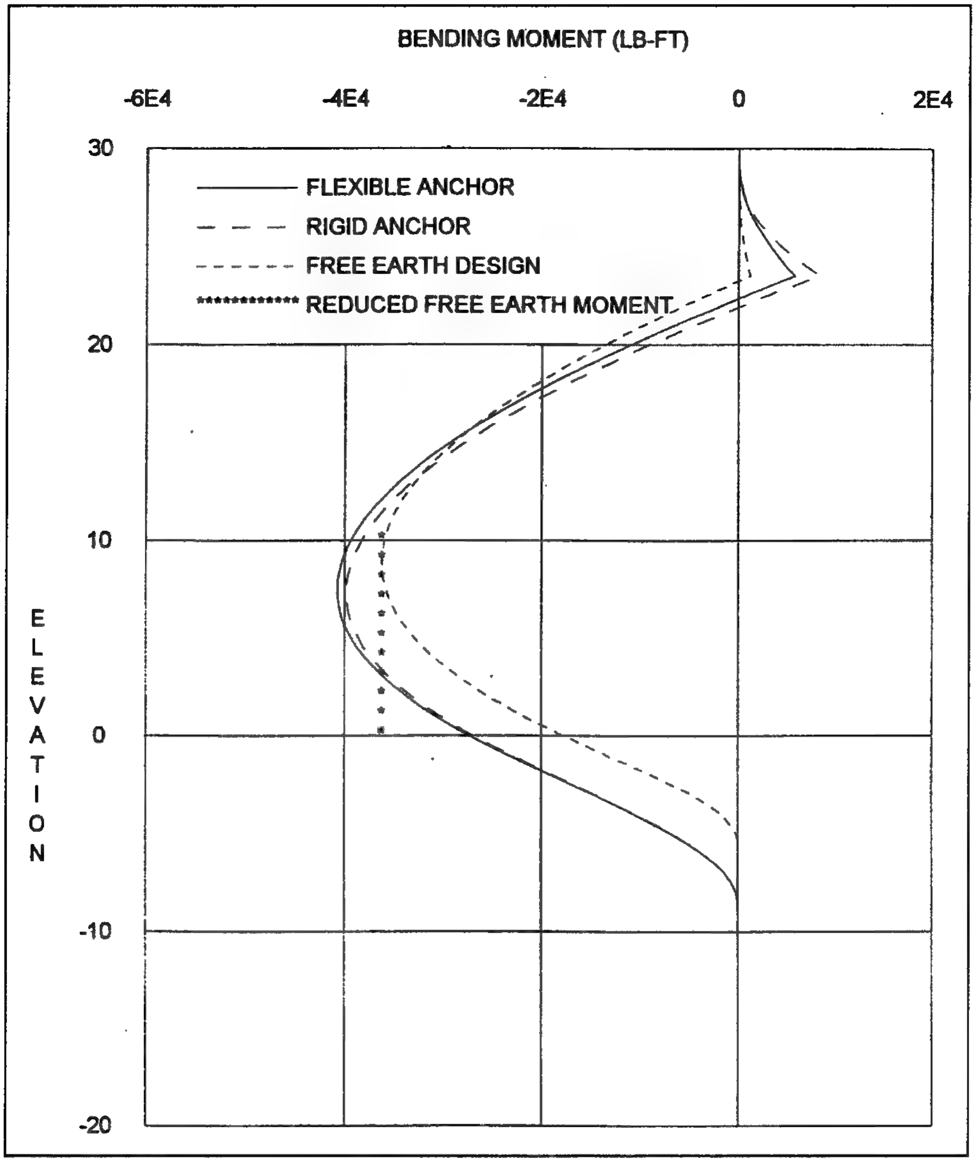

Figure 14. Bending moments for wall friction = 0.7*PHI for 30-ft wall

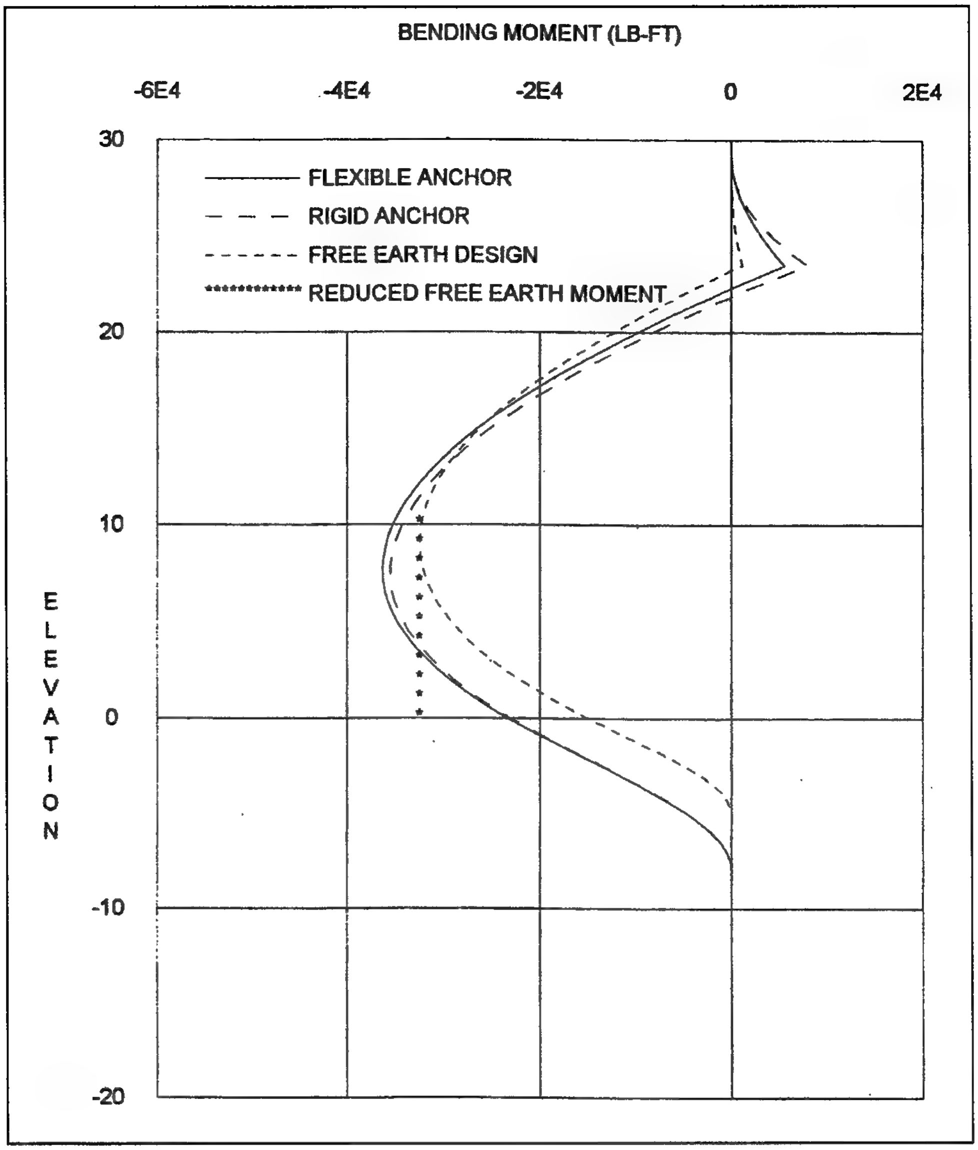

Figure 15. Bending moments for wall friction = PHI for 30-ft wall

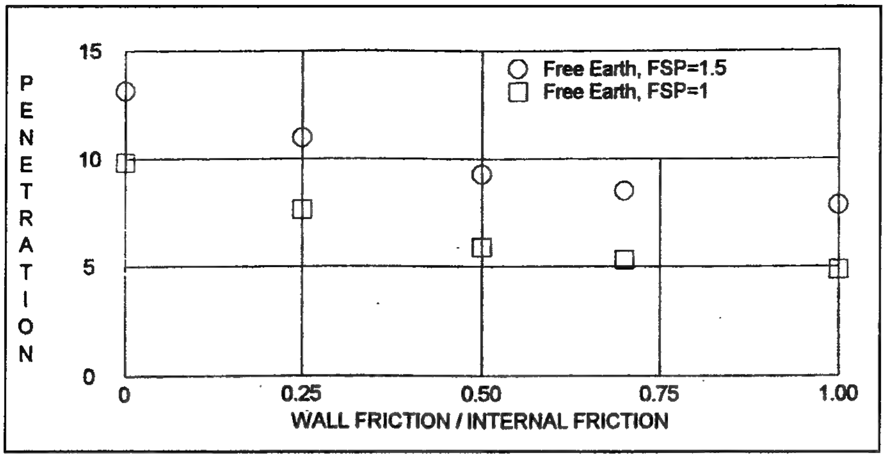

Figure 16. Effect of wall friction on penetration for 30-ft wall

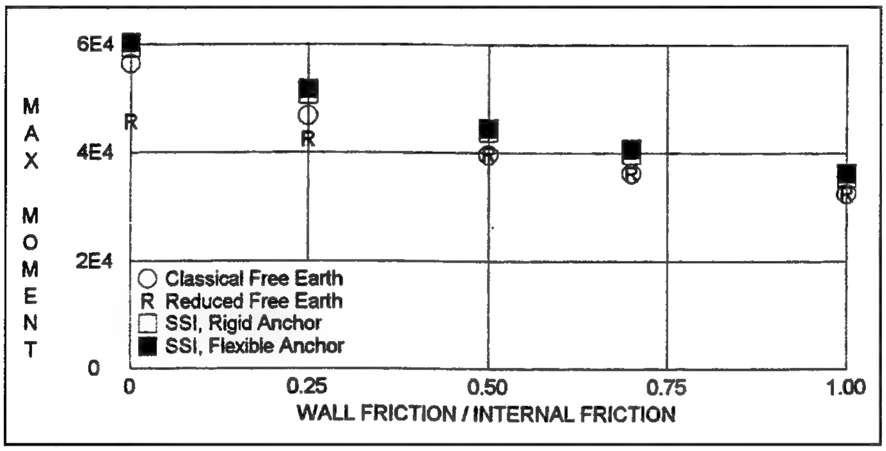

Figure 17. Effect of wall friction on maximum bending moment for 30-ft wall

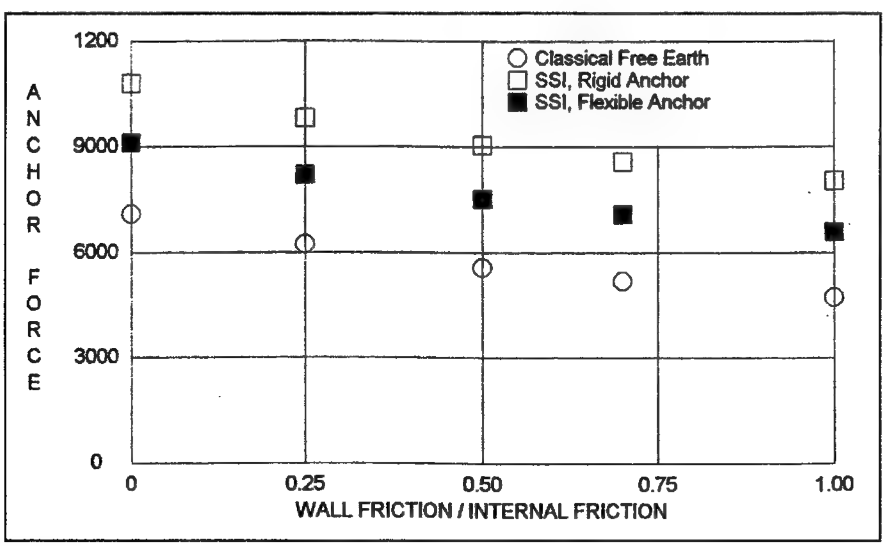

Figure 18. Effect of wall friction on anchor force for 30-ft wall

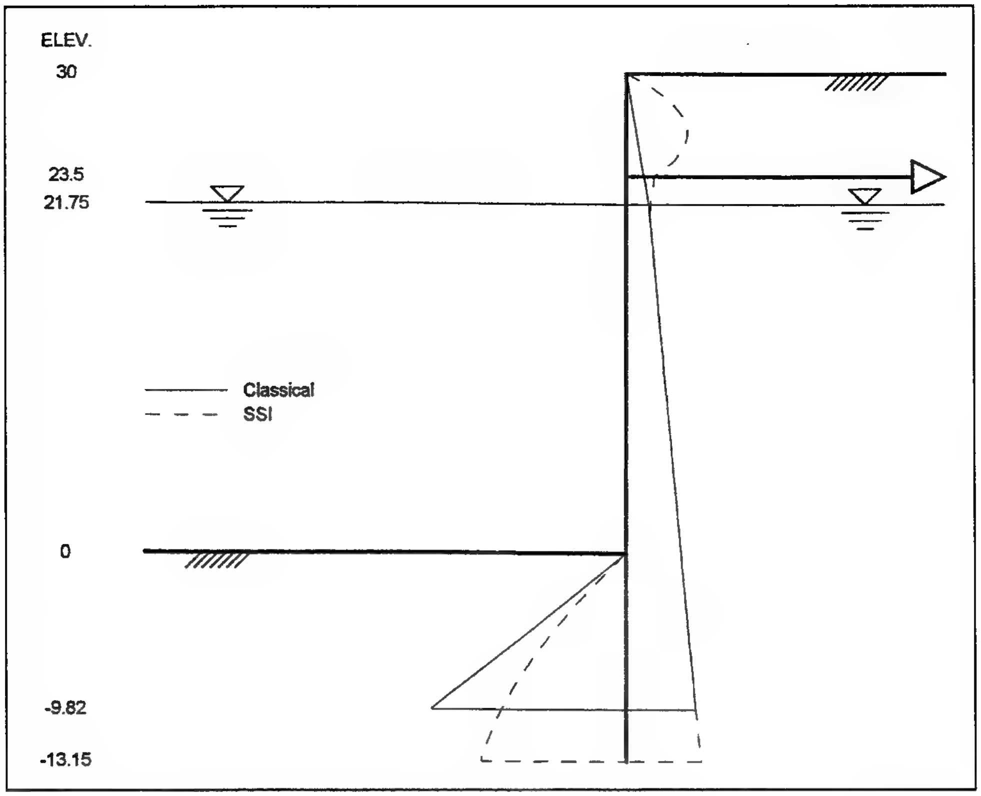

Figure 19. Soil pressures for Classical Case 1A and SSI Case 1AR for 30-ft wall

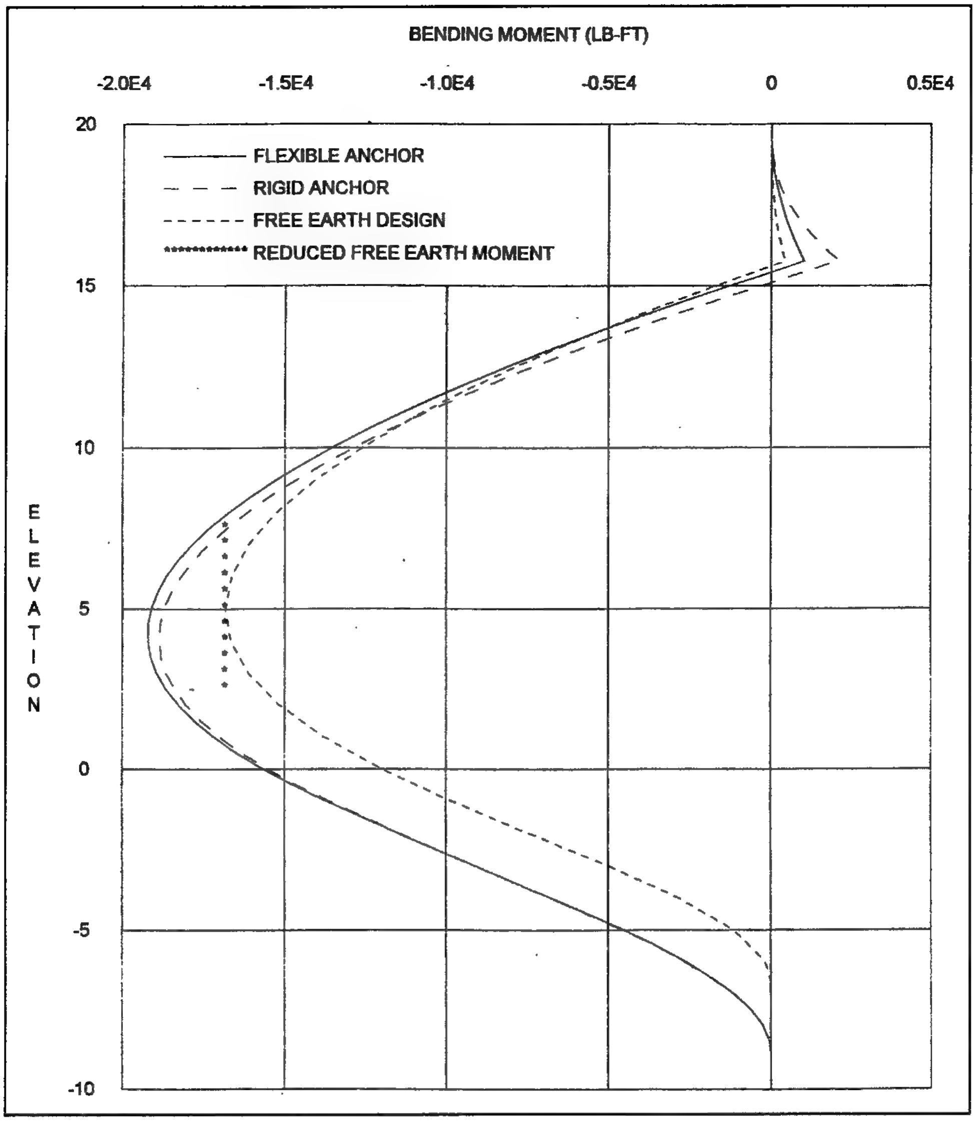

Figure 20. Bending moments for wall friction = 0 for 20-ft wall

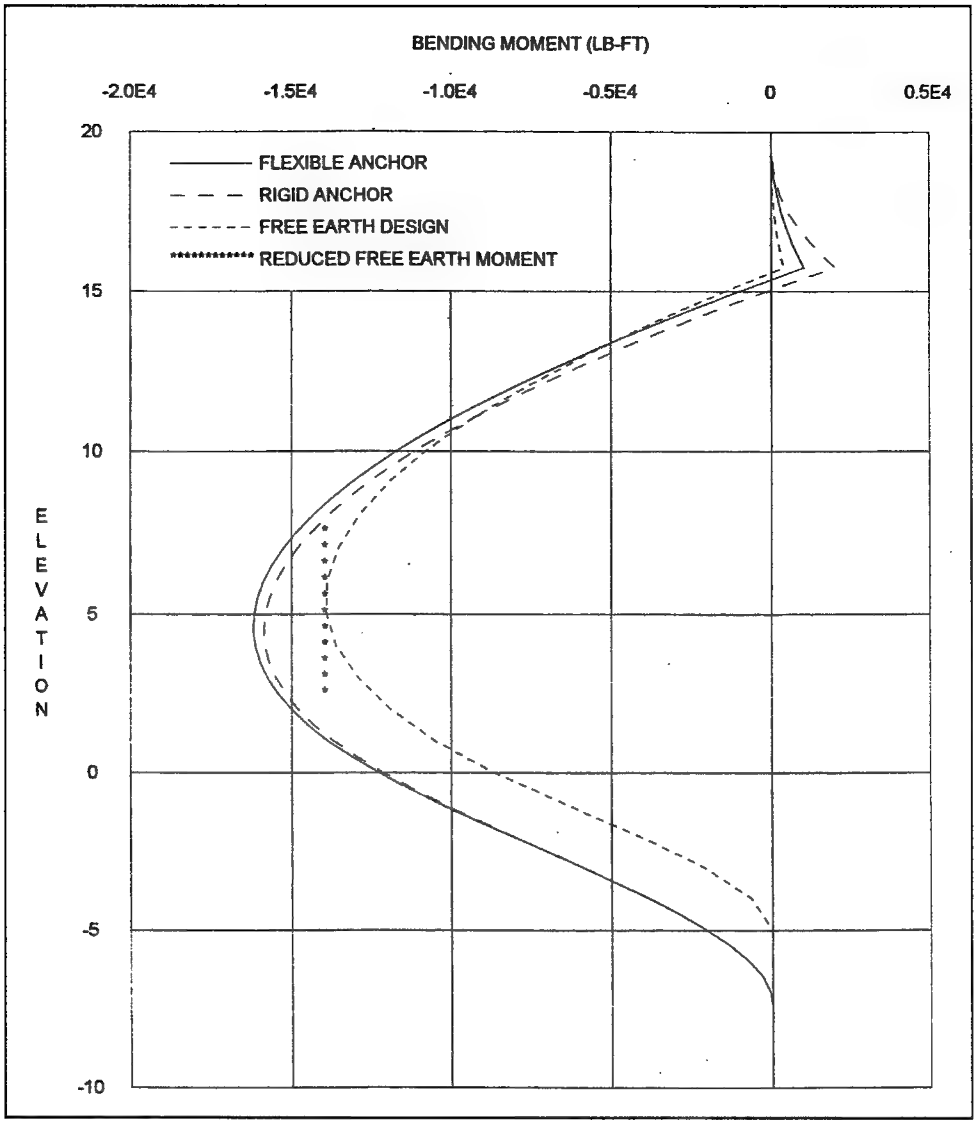

Figure 21. Bending moments for wall friction = PHI/4 for 20-ft wall

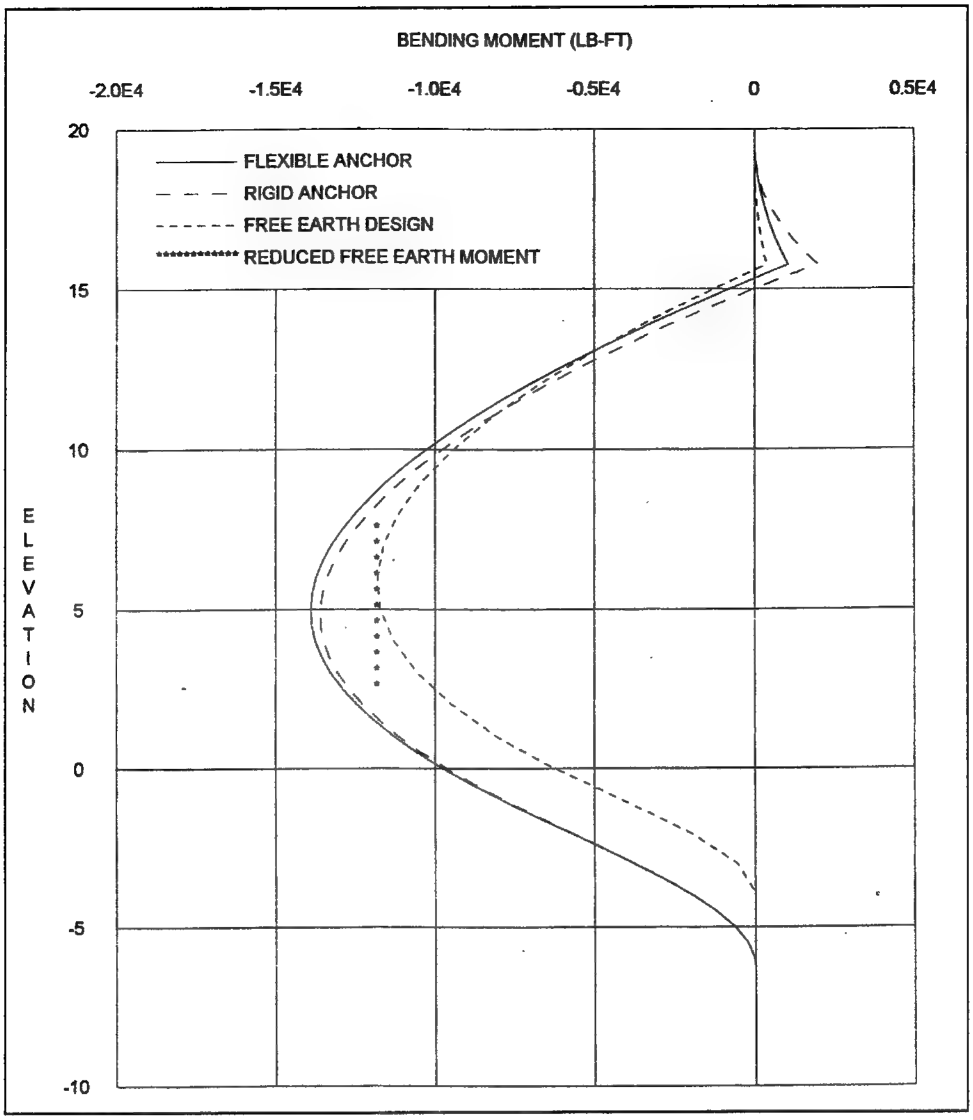

Figure 22. Bending moments for wall friction = PHI/2 for 20-ft wall

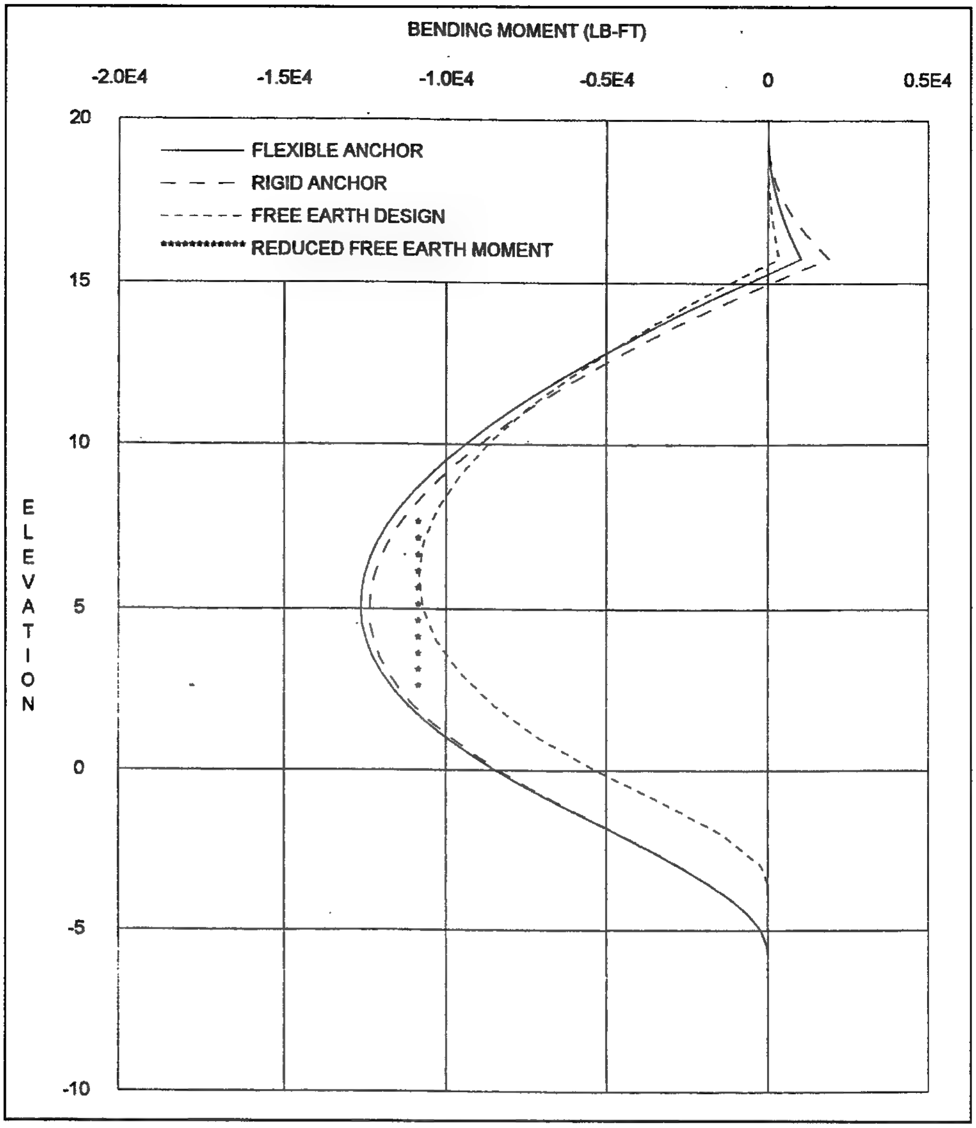

Figure 23. Bending moments for wall friction = 0.7*PHI for 20-ft wall

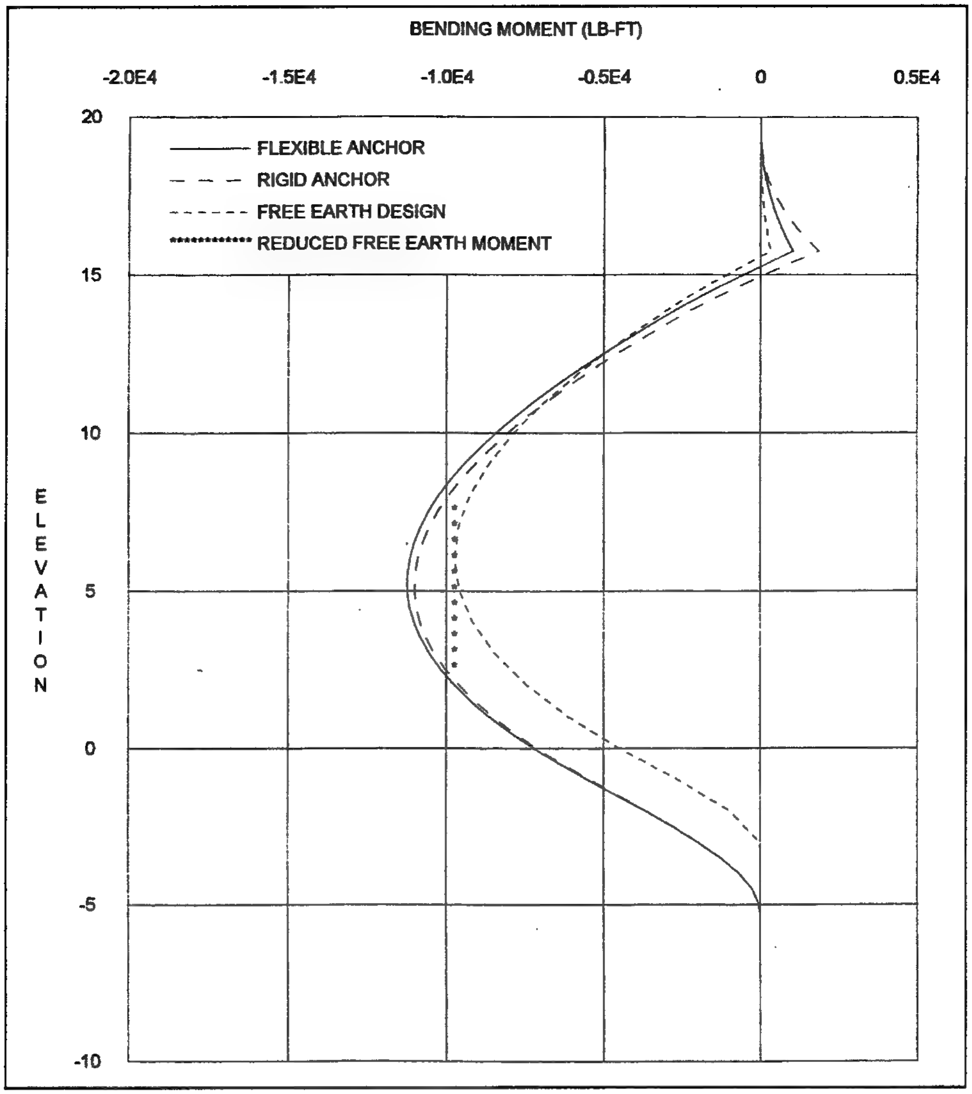

Figure 24. Bending moments for wall friction = PHI for 20-ft wall

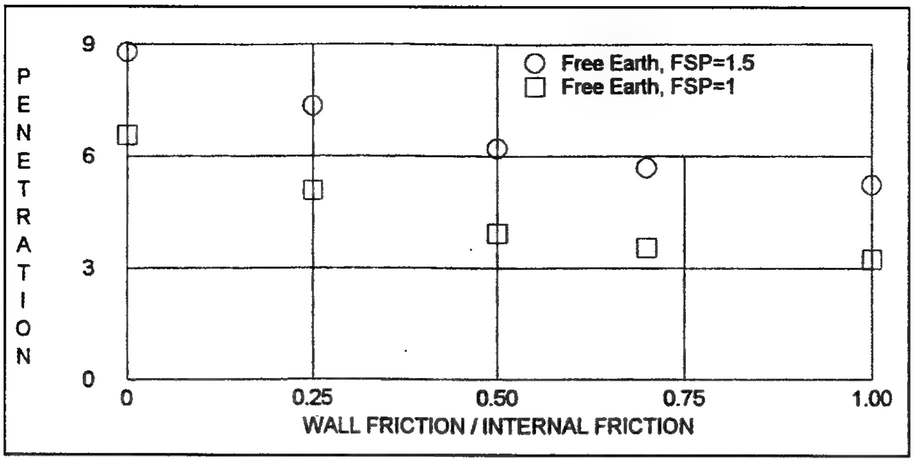

Figure 25. Effect of wall friction on penetration for 20-ft wall

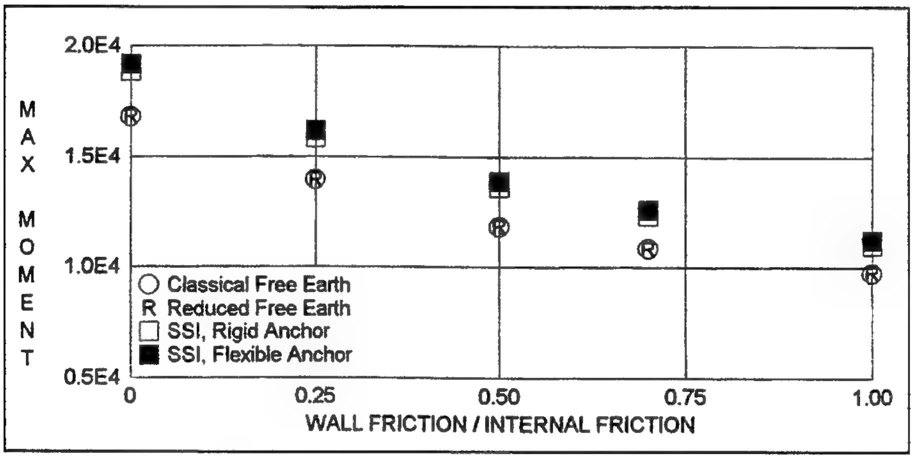

Figure 26. Effect of wall friction on maximum bending moment for 20-ft wall

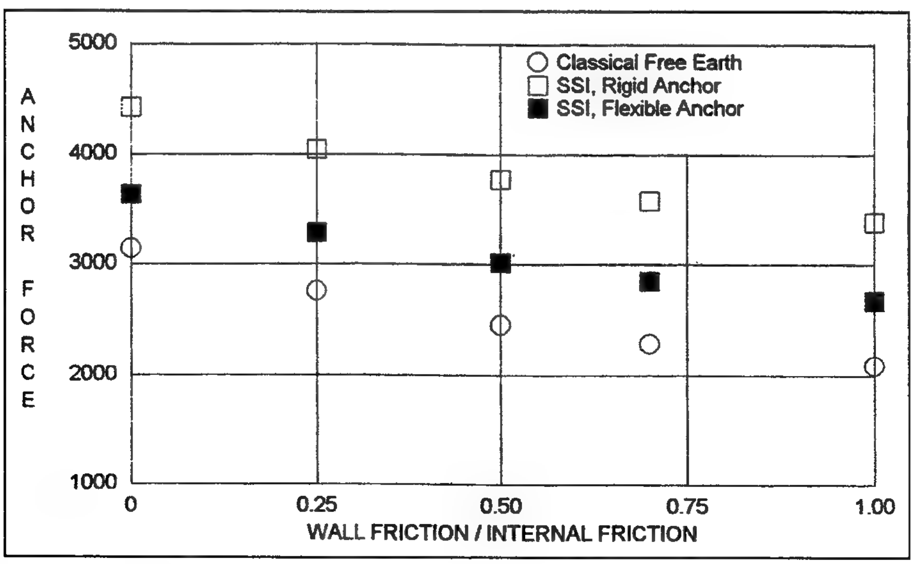

Figure 27. Effect of wall friction on anchor force for 20-ft wall

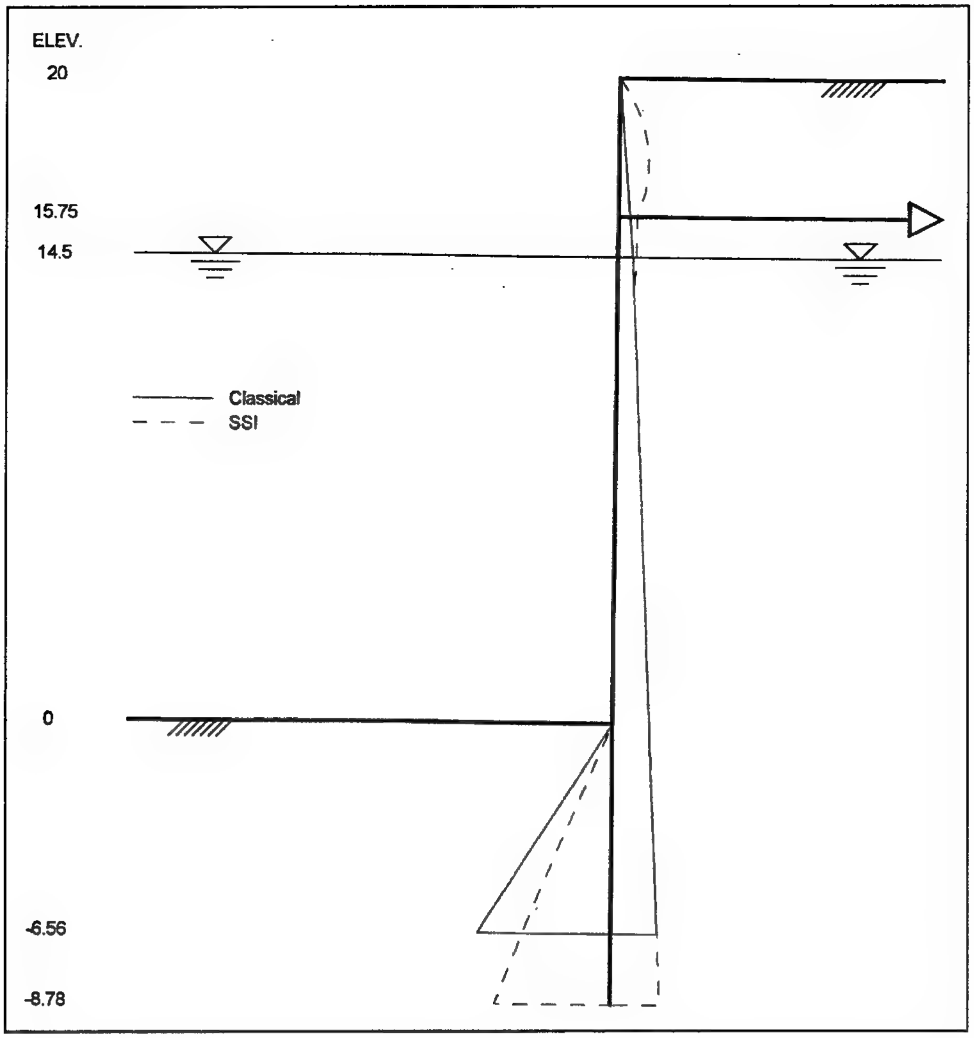

Figure 28. Soil pressures for Classical Case 1A and SSI Case 1AR for 20-ft wall

2 Comparison of Soil Pressure Calculation Methods for Surcharge Loads

Background

Users of the computer program CWALSHT (Dawkins 1991) have noted that significantly different design penetrations were produced when the program was forced to use a wedge method for soil pressure calculation for a system which ordinarily conformed to the requirements for the Coulomb coefficient method. Investigation of this problem indicated that the differences occurred as a result of procedures for incorporating the effects of surcharge loads. In the Coulomb coefficient method, surcharge effects are calculated using theory of elasticity equations; whereas, in the wedge methods, surcharges are added directly to the weight of each (trial) failure wedge.

System for Investigation

The anchored wall/soil system shown in Figure 29 was used for the investigation. The wall is imbedded in a uniform cohesionless soil with horizontal soils surfaces. The system conforms to the requirements for use of the Coulomb coefficient method; however, the program can be formed to use a wedge method by the inclusion of a second surface point on the horizontal soil surface. The presence of the anchor has no influence on soil pressures and serves only as a reference point.

Four surface surcharges on the right-side surface were investigated as indicated in Figure 29:

a. A uniform surcharge which is treated in essentially the same manner by both the coefficient and wedge methods.

b. A truncated ramp surcharge which produces an effective surface loading identical to a uniform surcharge. However, the contribution of this

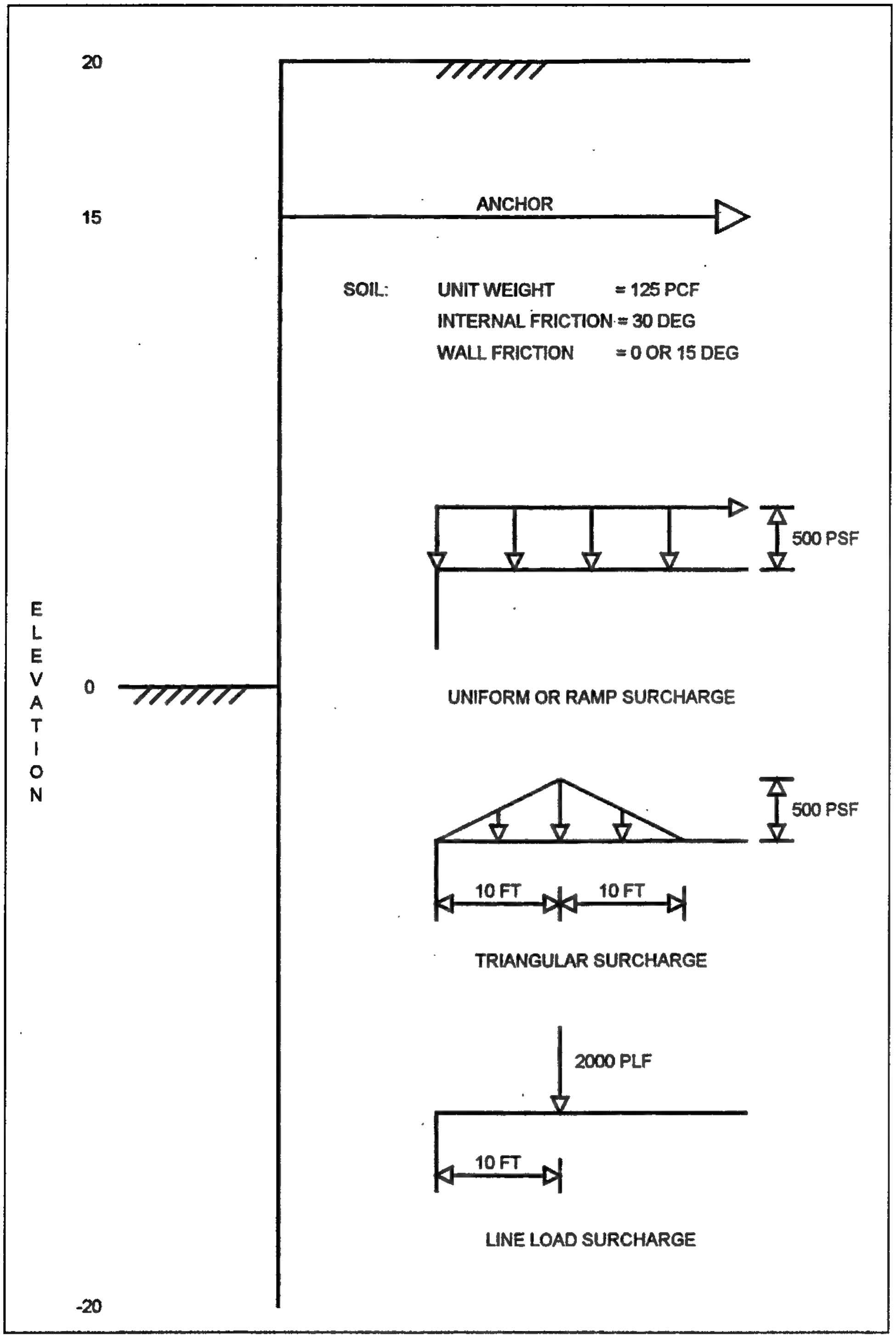

Figure 29. System for surcharge comparisons

surcharge is calculated from the theory of elasticity in the coefficient method while it is treated the same as a uniform load in the wedge methods.

c. A triangular surcharge.

d. A line surcharge.

Summary of Soil Pressure Calculation Methods

Coulomb coefficient method

Active and passive pressures are calculated from:

$$\rho_{A/P} = K_{A/P} \bullet \rho_v \tag{1}$$

where

$K_{A/P}$ = function of the angle of internal friction of the soil and the angle of wall/soil friction

ρ_v = effective vertical soils pressure including any uniform surcharge

Fixed surface wedge method

Active and passive forces are calculated for a fixed failure surface inclined at an angle from the vertical equal to

$$45^\circ \mp \phi/2$$

The active and passive forces are converted to soil pressures under the assumption that the difference between forces at successive calculation points is the resultant of a linearly varying pressure distribution in that interval.

Sweep search wedge method

Active and passive forces are calculated for a succession of trial failure surfaces by increasing the slope of the surface until the maximum active and minimum passive forces are determined for each point on the wall. Active and passive pressures are calculated as for the fixed surface method.

Comparison of Pressures for Wall/Soil Friction = 0

Uniform surcharge

Pressure distributions produced by the coefficient method and both wedge methods are essentially the same for the wall/soil system shown in Figure 29.

Truncated ramp surcharge

The pressures for the system with the truncated ram load are shown in Figures 30 and 31. Neither the coefficient method nor either wedge method recognizes the equivalence of the truncated ramp load and a uniform load. This accounts for the zero value of earth pressure at the ground surface.

At points below the ground surface, the pressures produced by both wedge methods are identical to those for a uniform surcharge. However, the coefficient method overestimates active pressures and underestimates passive pressures. The coefficient method calculates the contribution of the truncated ramp surcharge for both active and passive pressures, using the theory of elasticity, as a constant value at all depths equal to Q/2, where Q (=500 psf) is the intensity of the uniform portion of the ramp load. The total pressures become

$$\rho_A = \rho_v / 3 + Q/2 \tag{2}$$

and

$$\rho_P = \rho_v \bullet 3 + Q/2 \tag{3}$$

For a true uniform load, the coefficient method should produce:

$$\rho_A = \rho_v / 3 + Q/3 \tag{4}$$

and

$$\rho_P = \rho_v \bullet 3 + Q/3 \tag{5}$$

Triangular surcharge

Active and passive pressures for the triangular surcharge are shown in Figures 32 and 33. The small differences in pressures predicted by the wedge methods are attributable to the assumed angle of the failure plane of 30 deg from the vertical for active pressures and 60 deg for passive pressures in the fixed surface method, while the sweep search method varies the angle until limit values are attained.

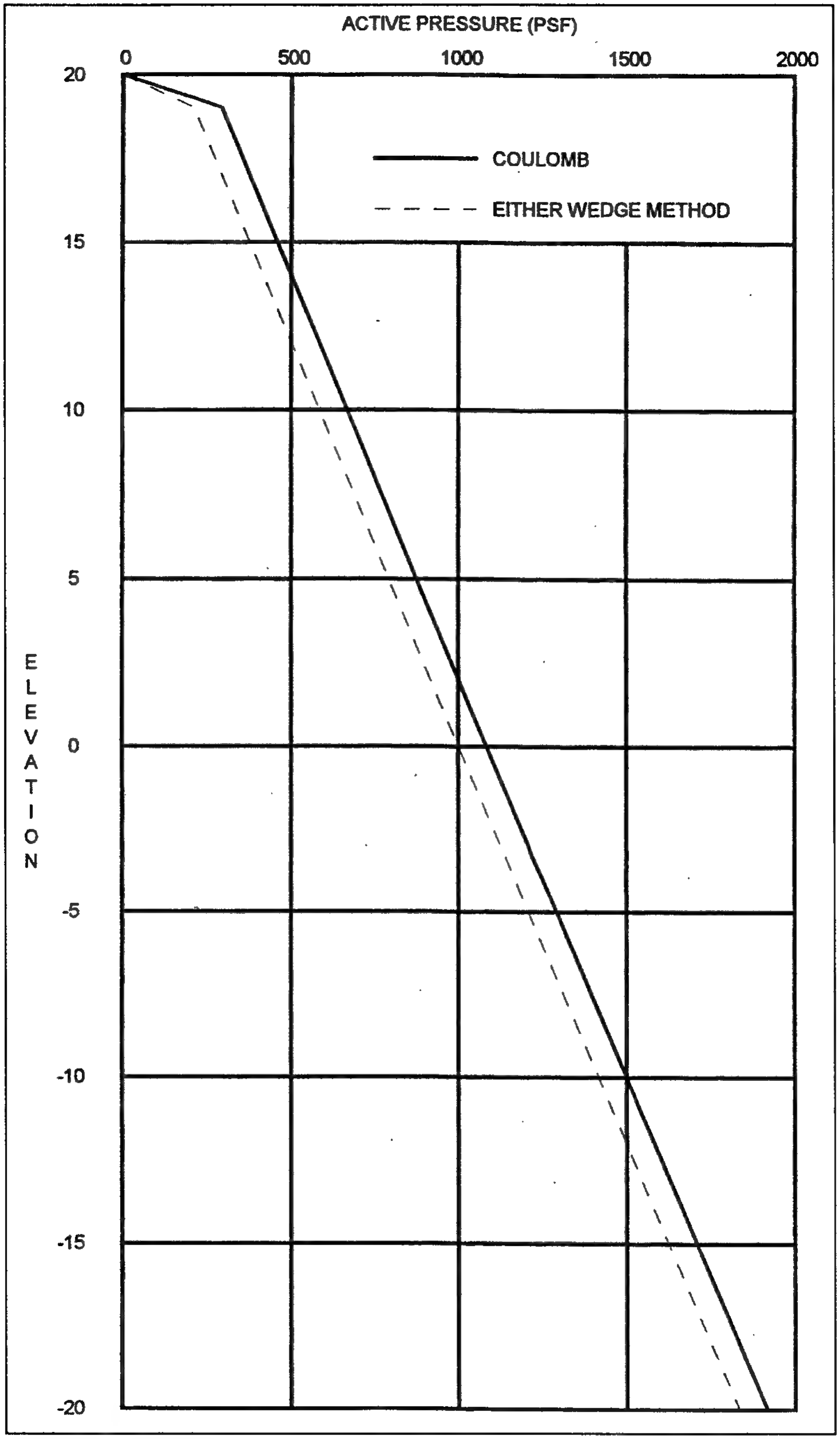

Figure 30. Comparison of active pressures as a result of "ramp" surcharge and wall friction = 0

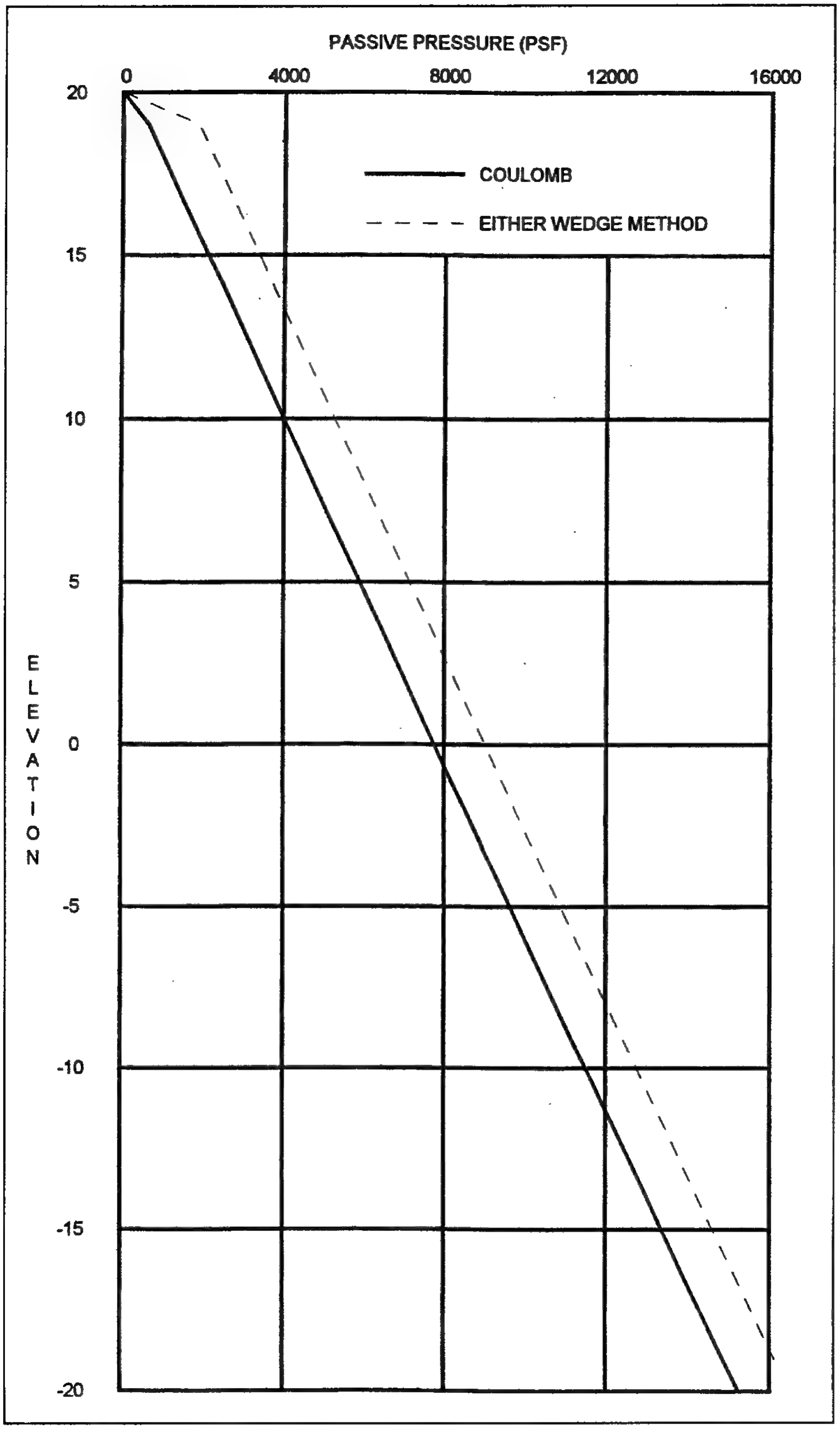

Figure 31. Comparison of passive pressures as a result of "ramp" surcharge and wall friction = 0

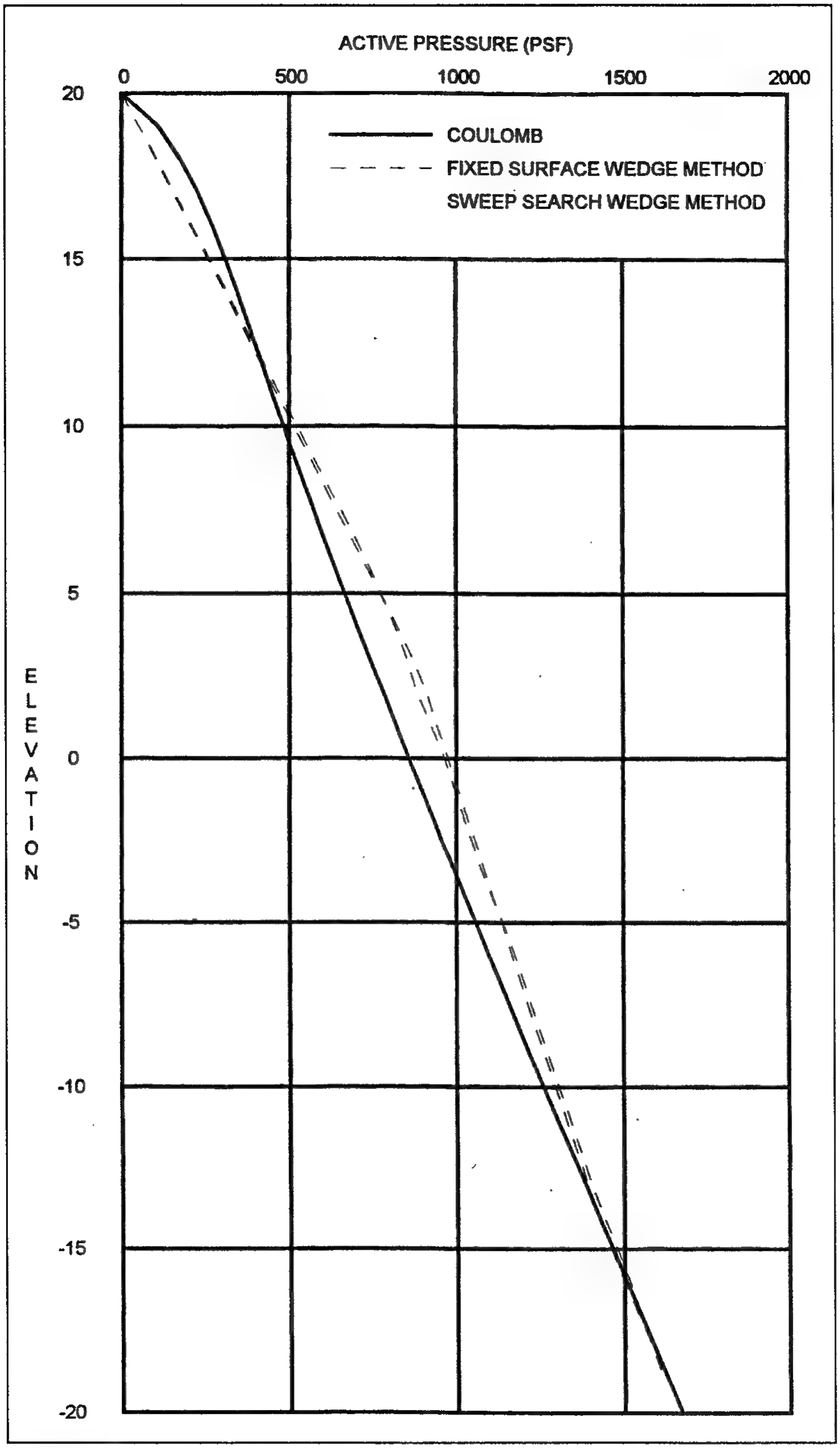

Figure 32. Comparison of active pressures as a result of triangular surcharge and wall friction = 0

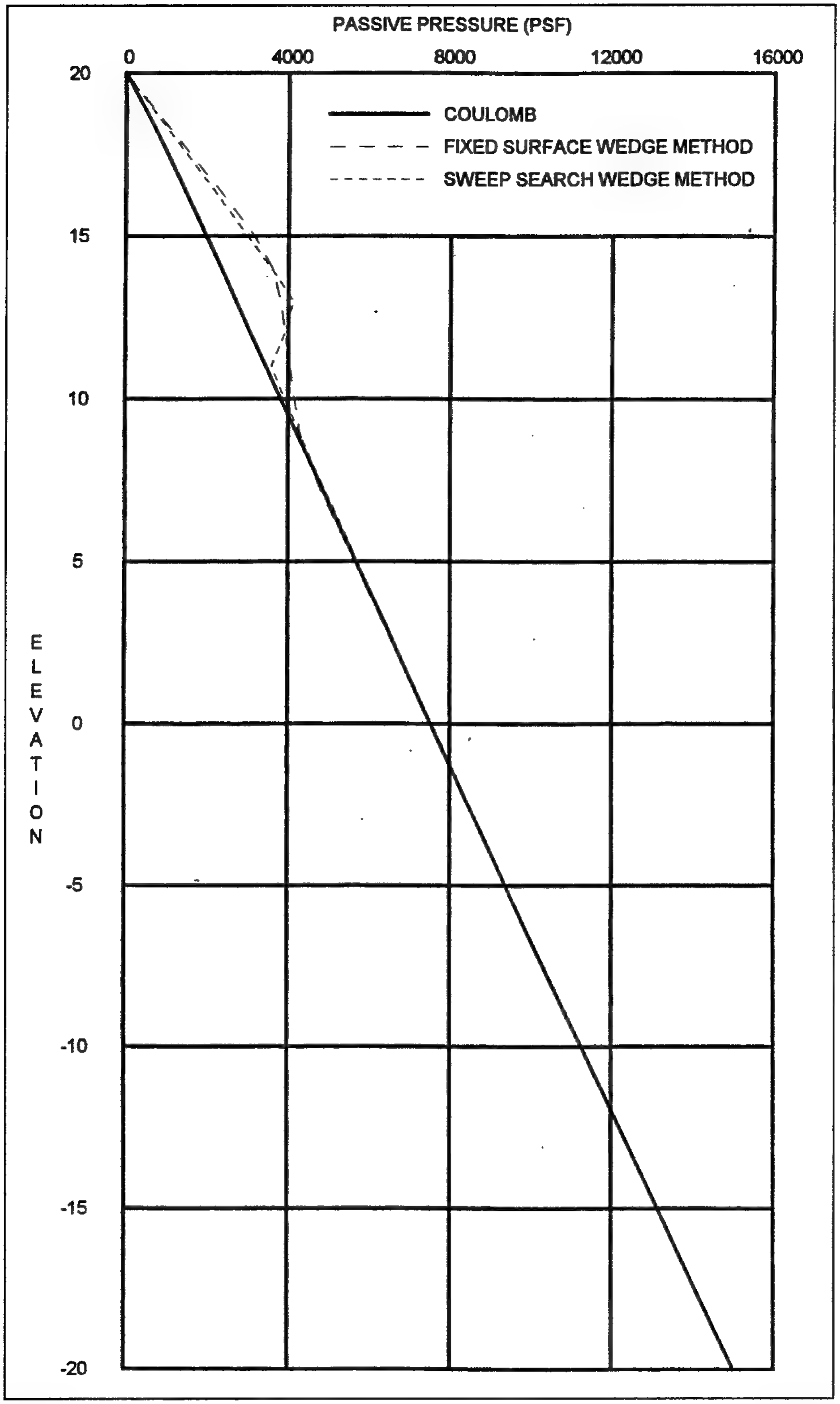

Figure 33. Comparison of passive pressures as a result of triangular surcharge and wall friction = 0

Line load surcharge

Pressures resulting from a line load are shown in Figures 34 and 35. The "blips" in pressures calculated by the wedge methods occur as the line load is encountered by the (trial) wedge at any point. Once the line load is incorporated in the wedge, any additional weight of the wedge is solely due to additional soil. Because the pressure is assumed to be a result of the difference in forces at adjacent points, the pressures from the wedge methods revert to the values which would be produced without the line surcharge.

Comparison of Pressures for Wall/Soil Friction = 15 deg

Uniform surcharge

Pressures for a uniform surcharge for all methods may be inferred from the pressures shown in Figures 36 and 37. Pressures produced by the coefficient method are identical to those predicted by the sweep search wedge method. The pressures from the fixed surface wedge method differ from those for the other two procedures because of the assumed fixed angle of inclination of the failure plane. For the coefficient method and the sweep search method, the limiting conditions occur at angles with the vertical of ~33 deg for active pressures and ~69 deg for passive effects compared to 30 and 60 deg, respectively, for fixed surface wedge method.

Truncated ramp surcharge

As for the case of zero wall friction, the coefficient method uses effective active and passive coefficients of 1/2 for the contribution of the surcharge. For a wall friction angle of 15 deg, the coefficients should be ~0.29 and ~4.8 for active and passive effects, respectively.

Triangular surcharge

Pressures resulting from the triangular surcharge for a wall friction of 15 deg are shown in Figures 38 and 39. Active pressures exhibit similar characteristics to those for the case with no wall friction with little differences between fixed surface and, sweep search wedge methods. The sweep search method indicates high pressures near the surface as compared to the coefficient method. Because the resultant of the higher sweep search pressure is very near the location of the anchor, little difference in design penetrations for the coefficient method and the sweep search method would be expected.

The fixed surface wedge method indicates higher passive pressures than either of the other methods at all depths. Again, the difference is attributable to the fixed angle assumed by this procedure.

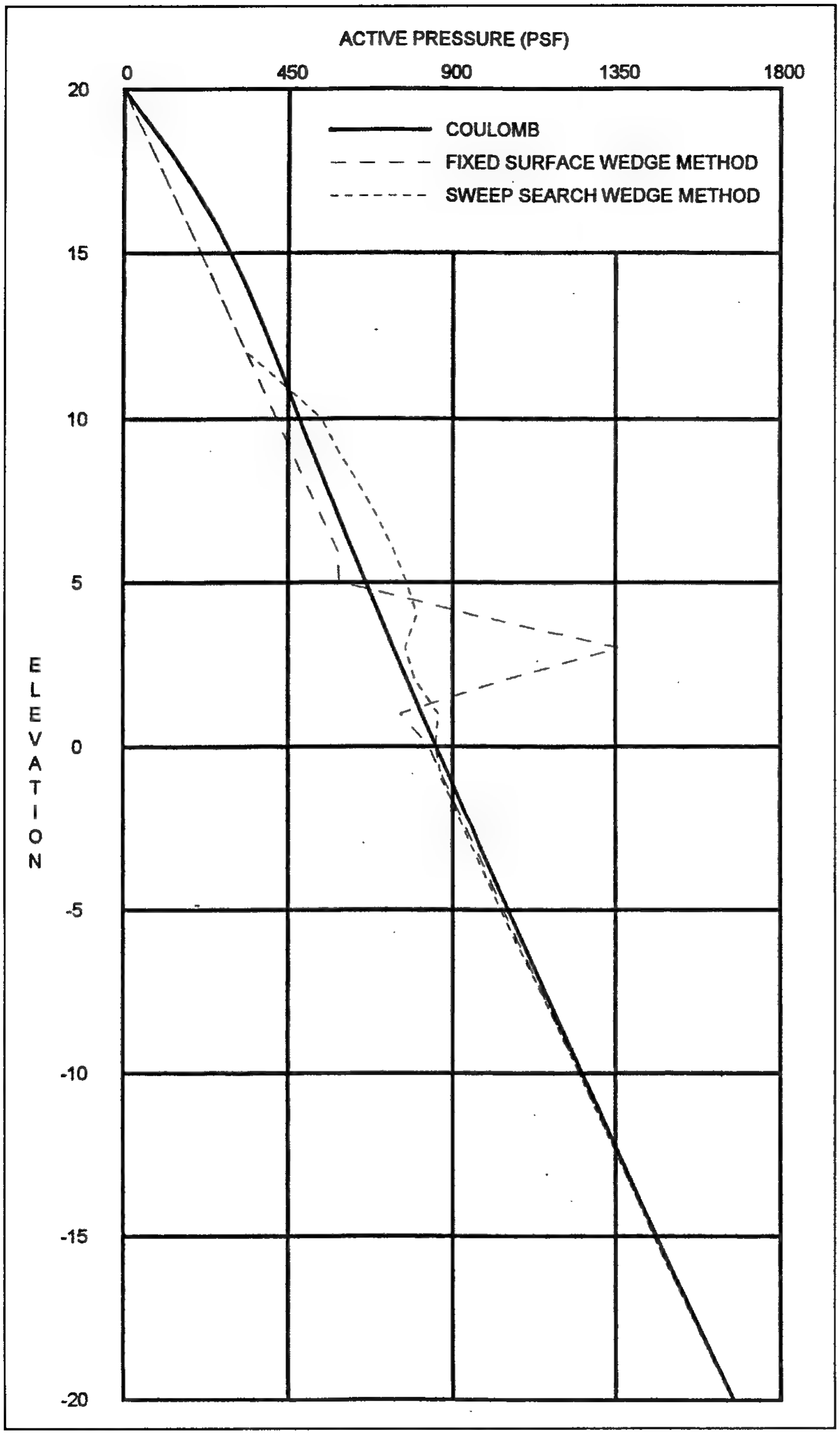

Figure 34. Comparison of active pressures as a result of line load surcharge and wall friction = 0

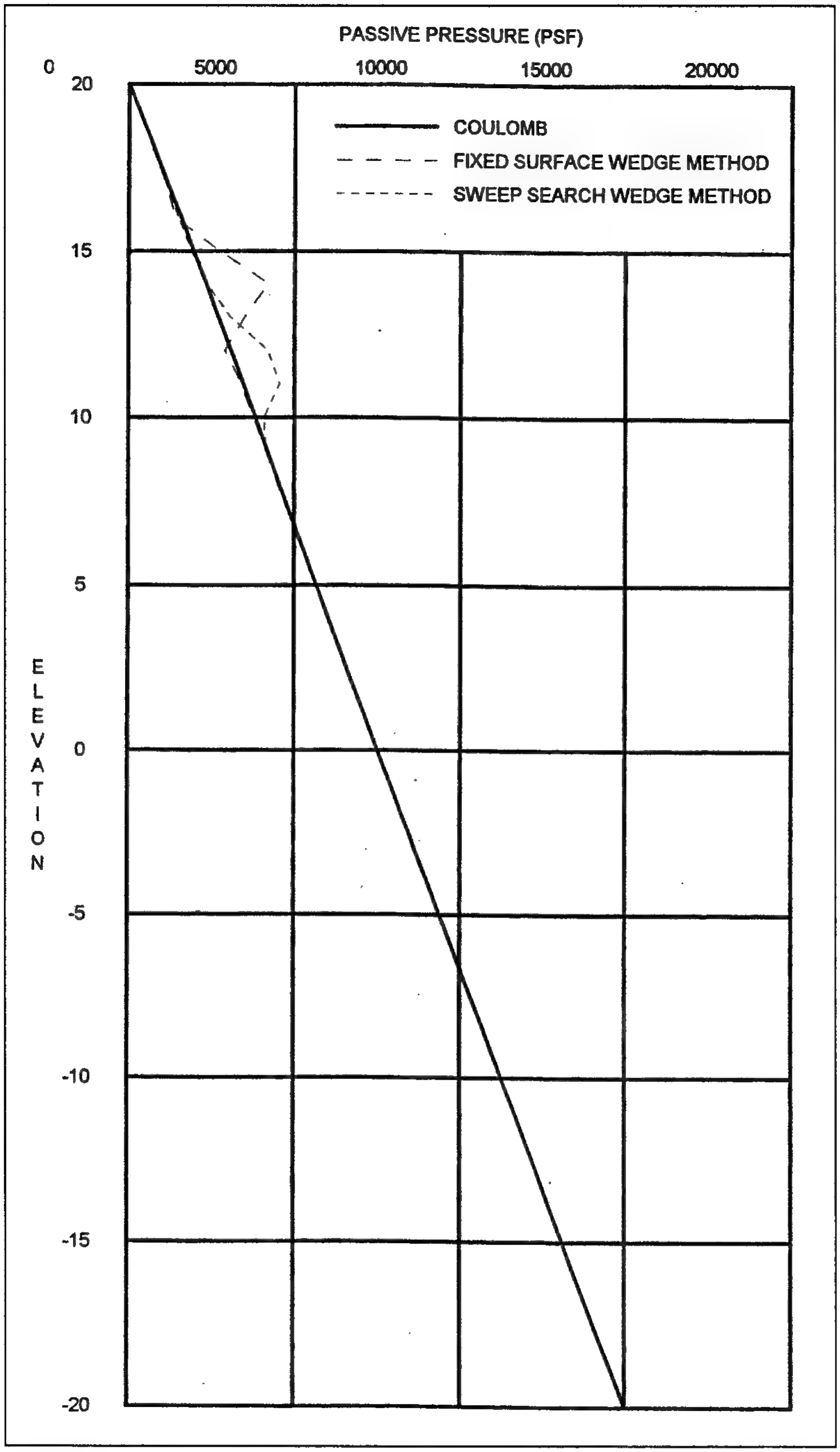

Figure 35. Comparison of passive pressures as a result of line load surcharge and wall friction = 0

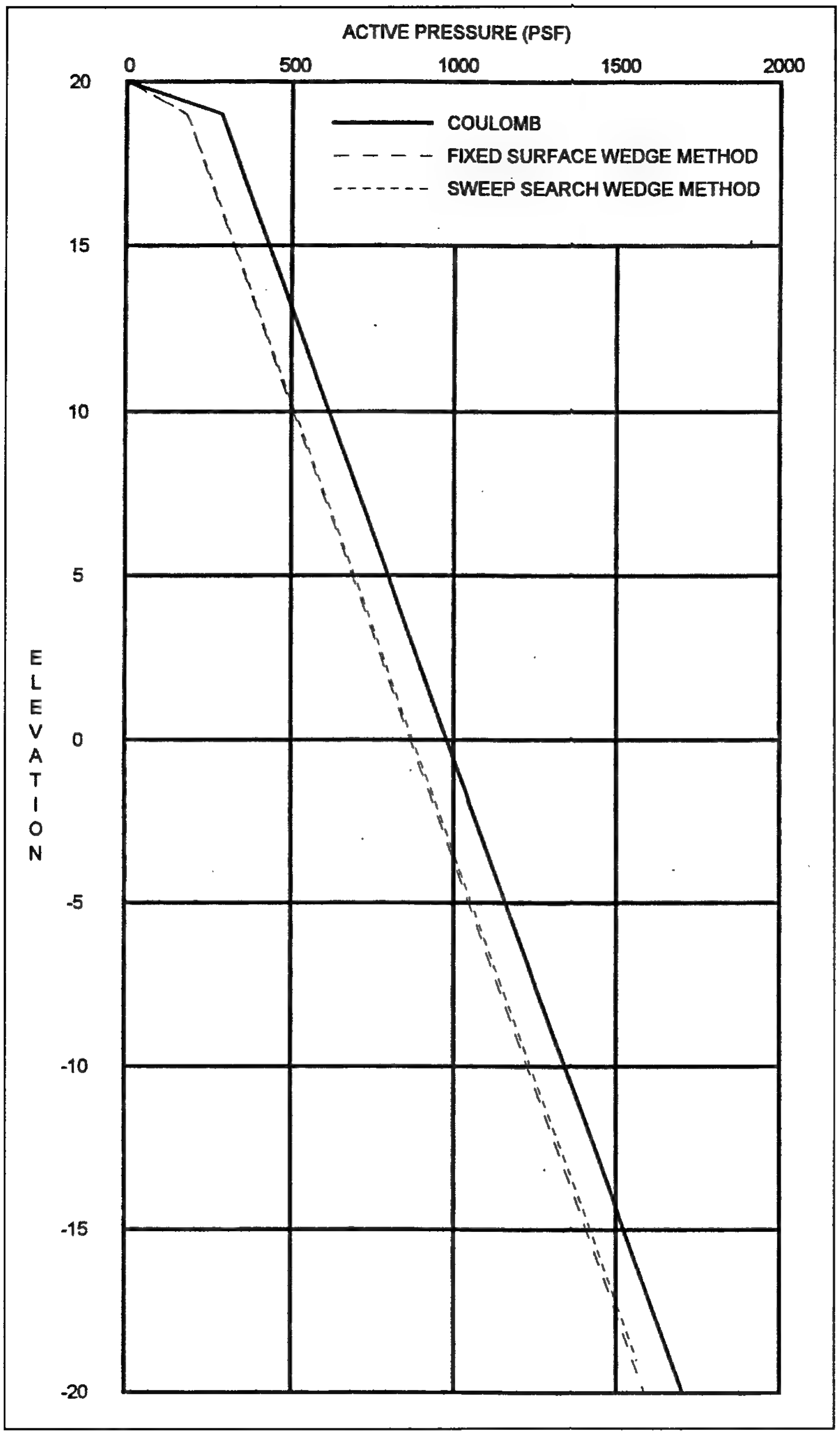

Figure 36. Comparison of active pressures as a result of "ramp" surcharge and wall friction = 15 deg

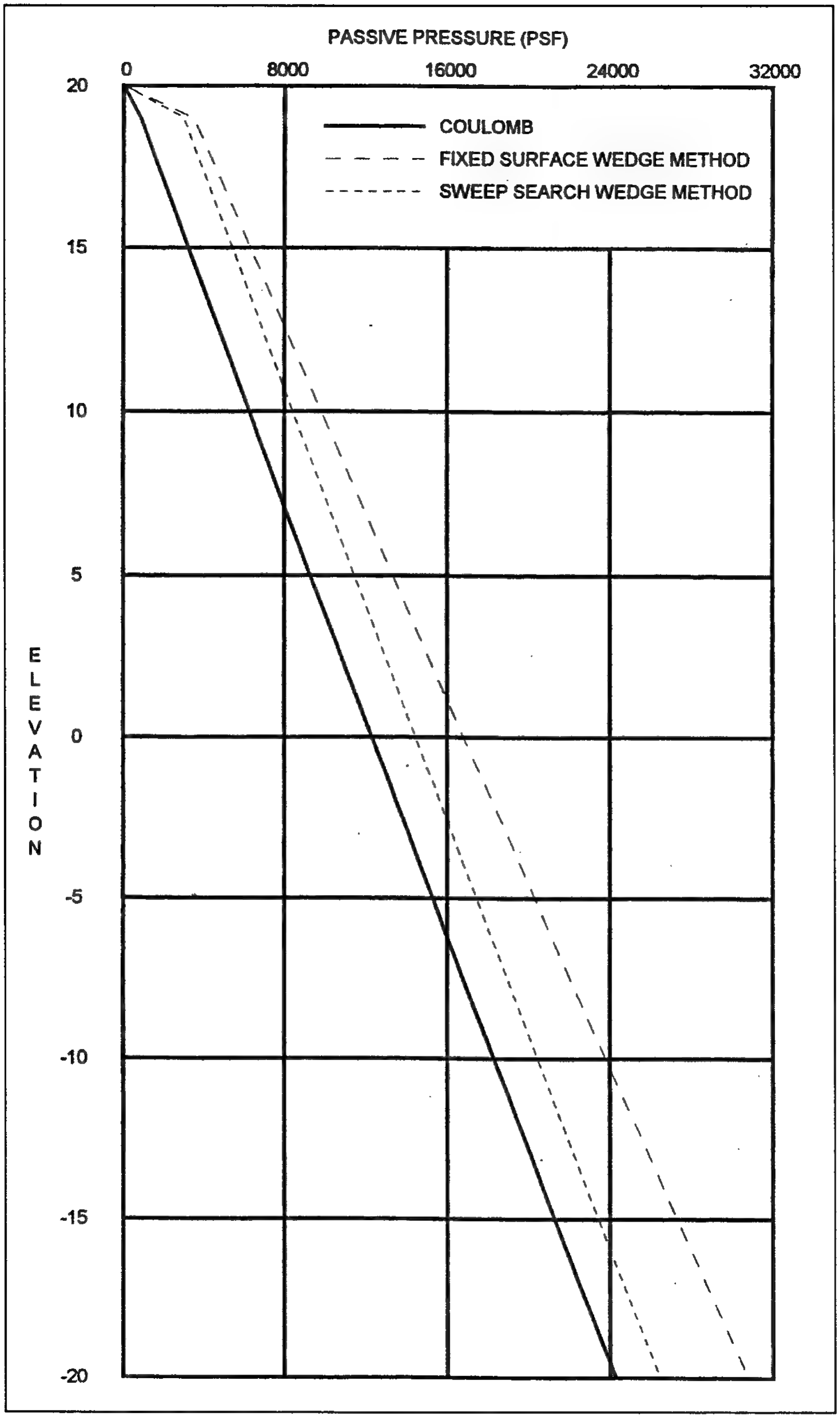

Figure 37. Comparison of passive pressures as a result of "ramp" surcharge and wall friction = 15 deg

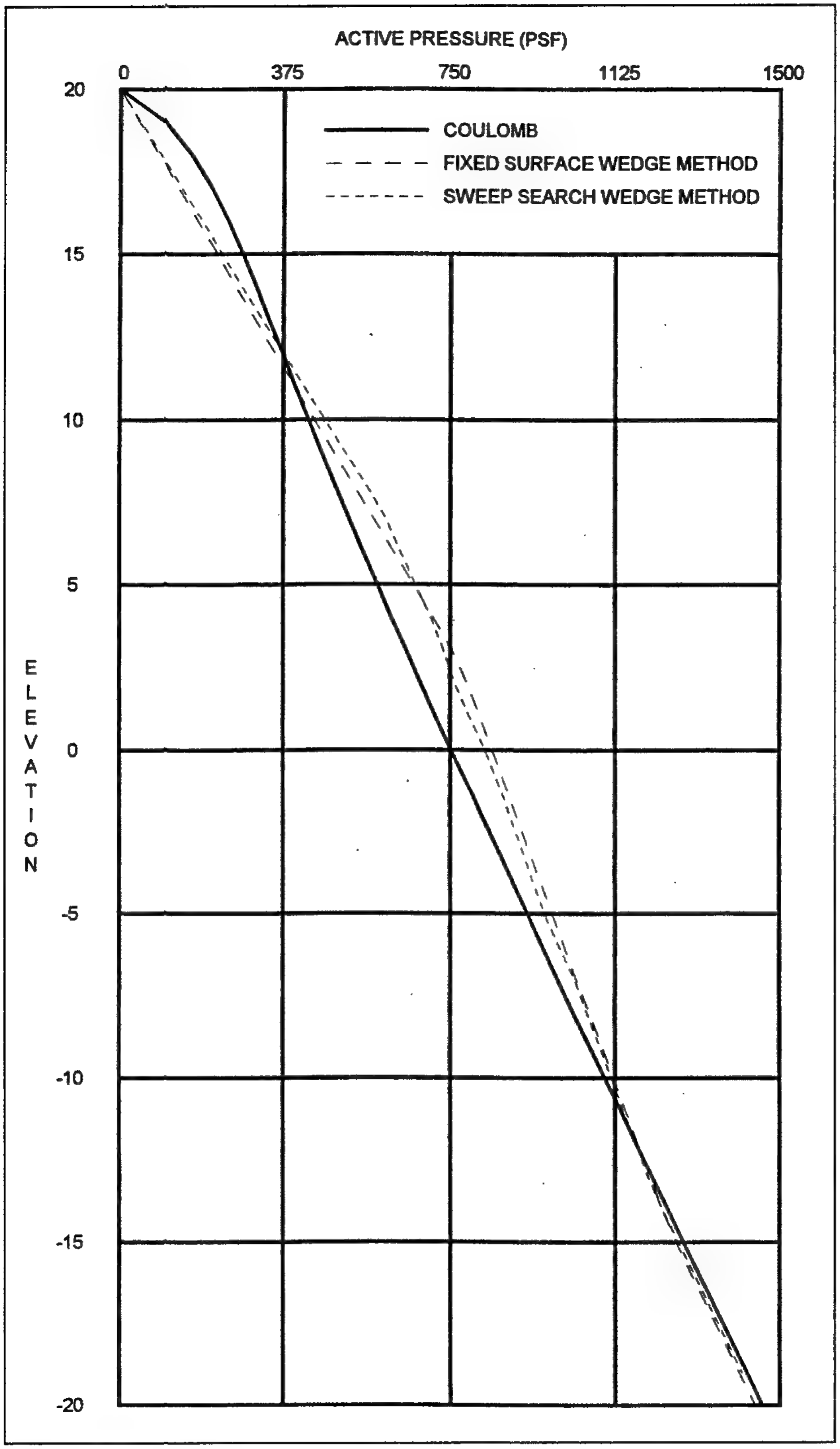

Figure 38. Comparison of active pressures as a result of triangular surcharge and wall friction = 15 deg

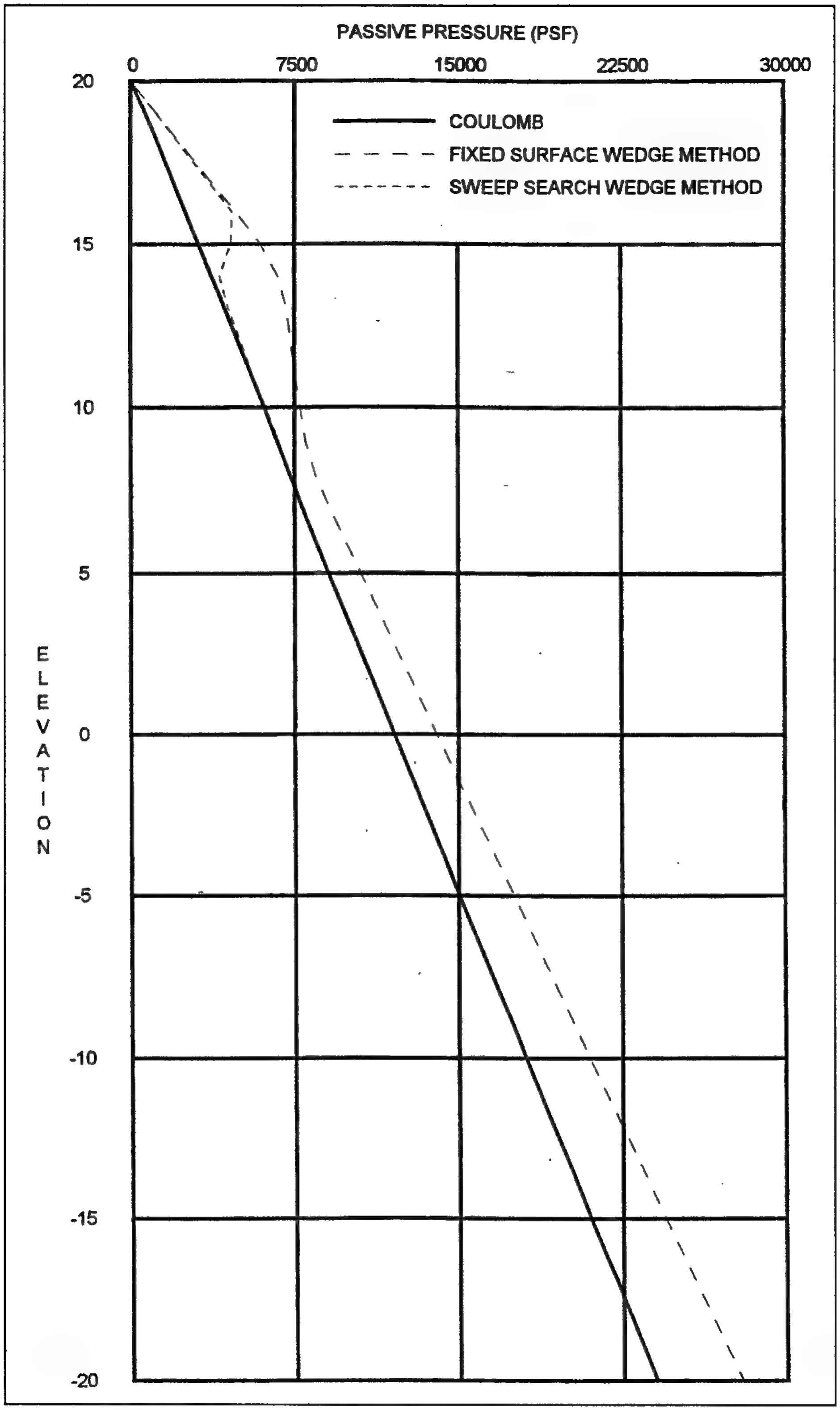

Figure 39. Comparison of passive pressures as a result of triangular surcharge and wall friction = 15 deg

Line load surcharge

The pressures shown in Figures 40 and 41 exhibit the same characteristics as those for the case without wall friction. The deviation of the passive pressures predicted by the fixed surface wedge method is a result of the assumed angle of the failure surface.

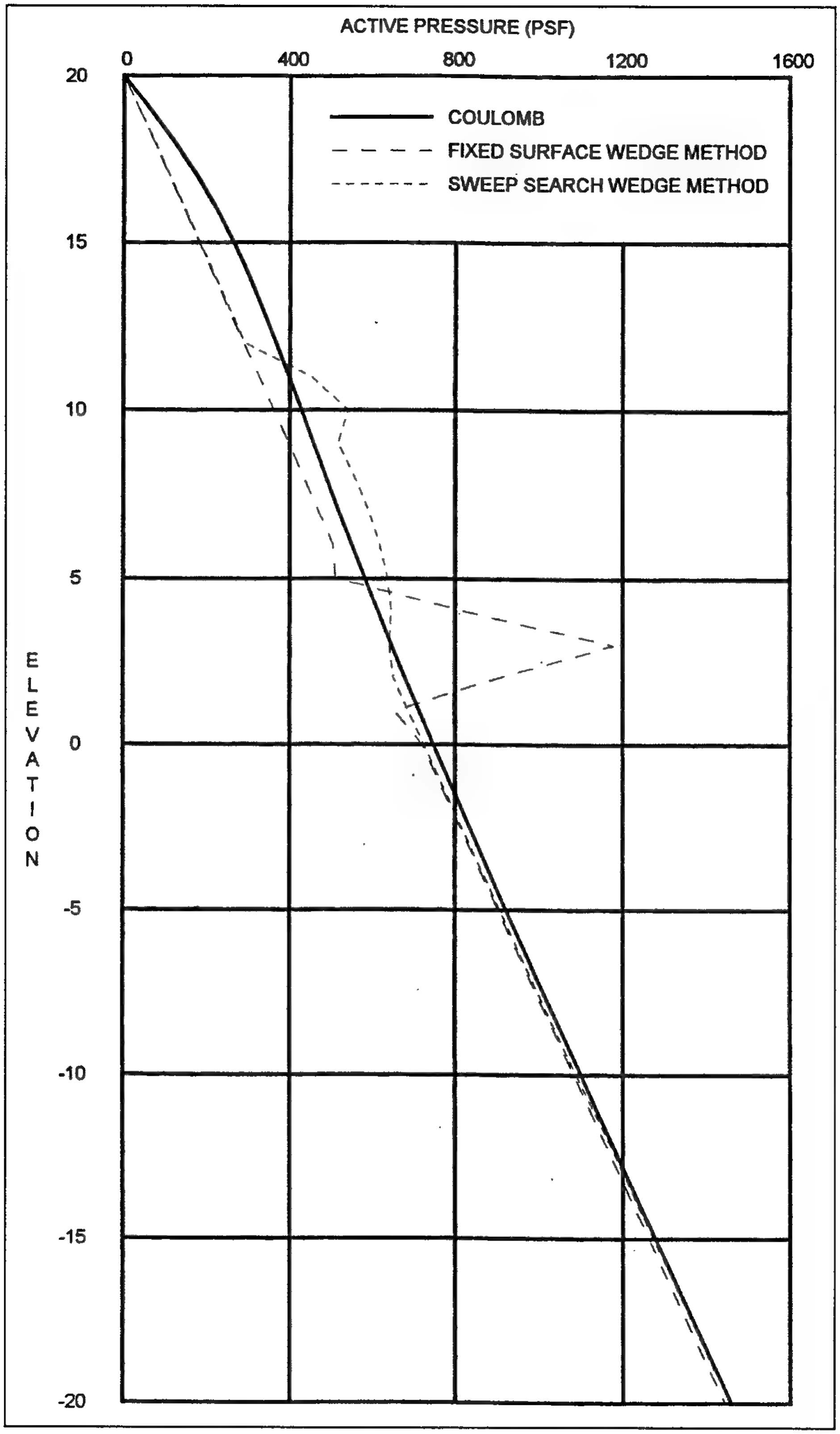

Figure 40. Comparison of active pressures as a result of line load surcharge and wall friction = 15 deg

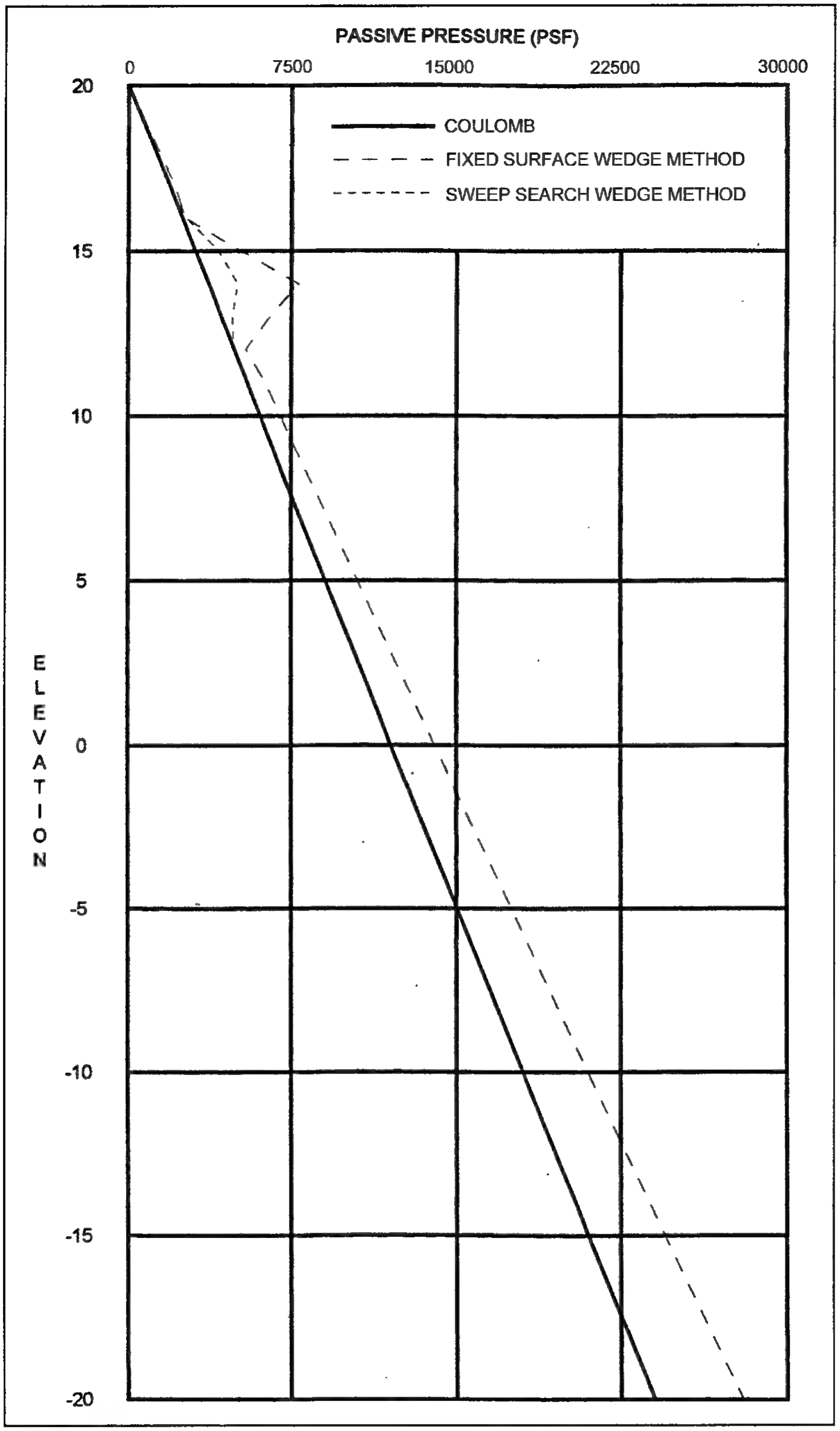

Figure 41. Comparison of passive pressures as a result of line load surcharge and wall friction = 15 deg

3 Comparison of Moment Reduction Coefficient Curves for Anchored Sheet-Pile Walls in Sand

Background

HQ, Department of the Navy (1982), Rowe (1952, 1957), Bowles (1977), and U.S. Steel Corp (1975) present curves of bending moment reduction coefficients to be applied to the bending moment calculated by the classical Free Earth Method of anchored wall design to account for sheet-pile flexibility. The curves shown in Figure 13-10a (Bowles 1977) appear to be identical to those presented in Figures 13d and e (Rowe 1952) (subsequently referred to as Rowe's curves). The curves for granular materials given in Figure 19 in "Design Manual 7.2" (HQ, Department of the Navy 1982) (subsequently referred to as NAVFAC curves) and those shown in Figure 27 (U.S. Steel 1975) are different from those shown by Rowe (1952) and Bowles (1977), although HQDOA (1994) is cited as the source of the curves presented in "Design Manual 7.2" (HQ, Department of the Navy 1982). There is no discussion of the methods employed to extract the curves in "Design Manual 7.2" (HQ, Department of the Navy 1982) from the data given by Rowe (1952). The principal differences in the two sets of curves are:

a. Rowe (1952) and Bowles (1977) give curves for "loose" sand and "dense" sand which account for the height of the wall and are implicity restricted as to position of the anchor with respect to the height of the wall (Figure 42).

b. "Design Manual 7.2" (Headquarters, Department of the Navy 1982) and U.S. Steel Corporation (1975) present only a single curve for each of "medium compact and coarse grained soils" and indicate no limitations on system configuration.

The Rowe's curves for "loose" and "dense" sands are compared with the NAVFAC curves in Figures 43 and 44. The NAVFAC curve for "medium compact and compact" soils appears to be approximately the average of the three

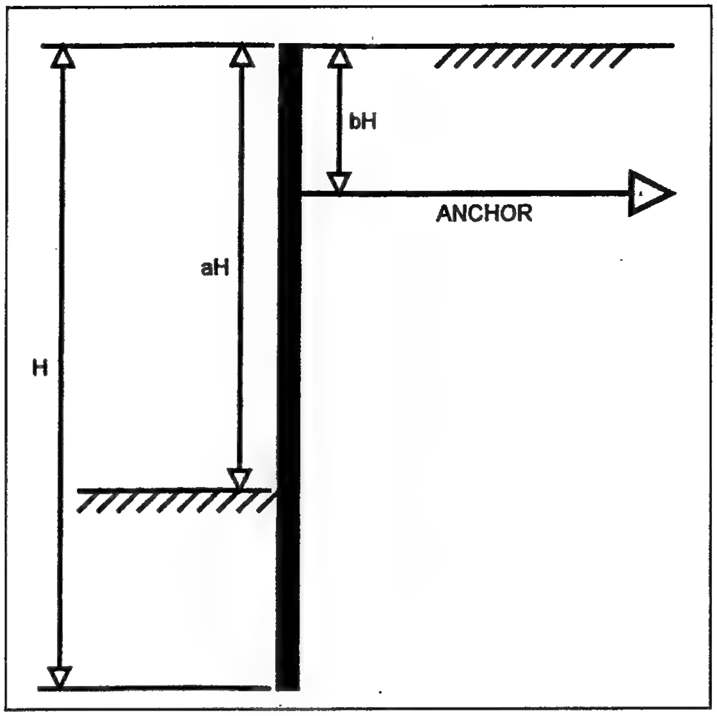

Figure 42. Notation for Rowe's moment reduction curves

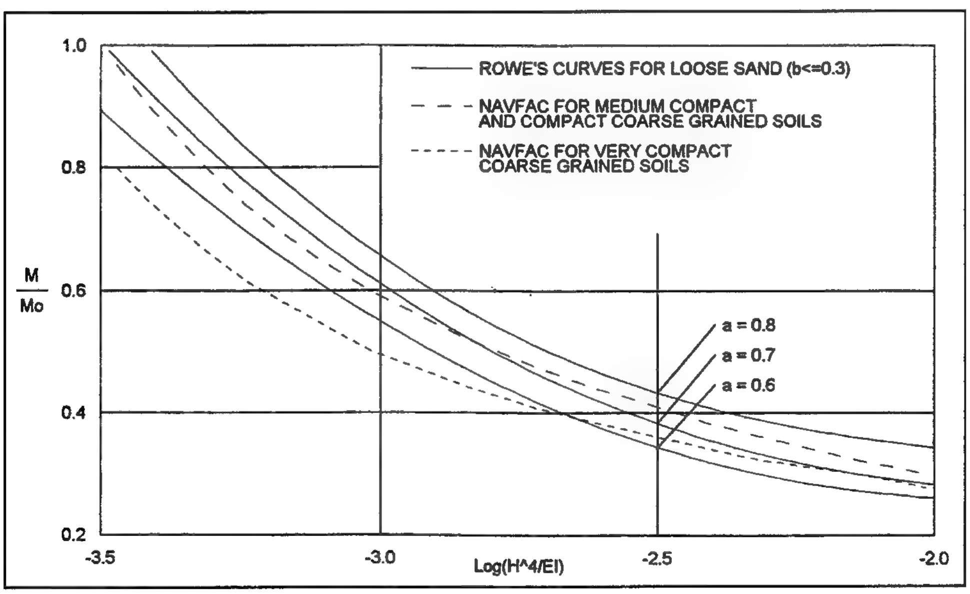

Figure 43. Comparison of Rowe's moment reduction curves for loose sand with NAVFAC curves

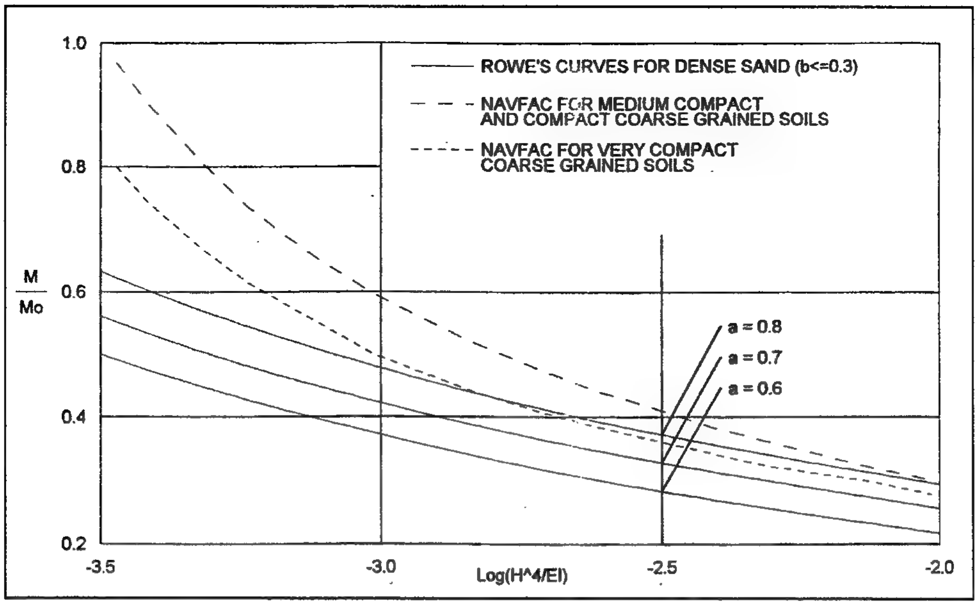

Figure 44. Comparison of Rowe's moment reduction curves for dense sand with NAVFAC curves

Rowe's curves for "loose" sand. However, the NAVFAC curve for "very compact" soils is considerably more conservative for stiffer walls ($\log(H^4/EI)$ < about –3) than Rowe's curves and approaches the average of Rowe's curves for more flexible walls.

Bowles (1977), Rowe (1957), and U.S. Steel Corporation (1975) provide moment reduction curves for sheet piles embedded in clays. Headquarters, Department of the Navy (1982) does not address moment reduction for clays.

Current Status

Rowe's (1952) curves for "loose" and "dense" sands are built into the CWALSHT computer program and are applied to the results of the Free Earth Method under the following conditions (see Figure 42 for notation):

a. The soil surface on the retained side of the wall is at the top of the wall.

b. The left-side soils is composed exclusively of one or more layers of cohesionless material. (Note: Rowe's (1952) curves were obtained from experimental data for strictly homogeneous soil systems.)

c. The exposed height of the wall conforms to $0.6 \leq a \leq 0.8$ (Figure 42). The curve for a system with a not equal to 0.6, 0.7, or 0.8 is obtained by linear interpolation between the two bounding curves.

d. The anchor position conforms to b ≤ 0.3.

e. The wall flexibility conforms to $-3.5 \leq \log(H^4/El) \leq -2.0$.

Rowe's (1957) curves for sheet-pile walls embedded in clay from Dawkins (1991) and Headquarters, Department of the Army (1994) are built into CWALSHT and are applied to the results of the Free Earth Method under the following conditions:

a. The soil surface on the retained side of the wall is at the top of the wall.

b. The left-side soils is composed exclusively of one or more layers of cohesive material. (Note: Rowe's curves were obtained from experimental data for strictly homogeneous systems.)

c. The exposed height of the wall conforms to 0.6 ≤ a ≤0.8 (Figure 42). The curve for a system with a not equal to 0.6, 0.7, or 0.8 is obtained by linear interpolation between the two bounding curves.

d. The stability number defined by

$$S_n = c/\rho_v\sqrt{1+C_a/c}$$

where

c = soil cohesion

ρ_v = vertical pressure in the right-side soil at the elevation of the left-side soil

C_a = wall/soil adhesion in the left-side soil.)

satisfies $0.5 \leq S_n \leq 2.0$.

e. The anchor position conforms b ≤ 0.3.

f. The flexibility number satisfies $-3.1 \leq \text{Log}(H^4/El) \leq -2.0$.

(Note: The curve for a not equal 0.6, 0.7, 0.8 and for $\text{Log}(H^4/El)$ not equal to -3.1, -2.6, or -2.0 is obtained by interpolation among the bounding curves.)

Recommendations

It would be desirable for all Corps of Engineers' design procedures to use the same moment reduction curves. However, because NAVFAC Design Manual 7.2 (Headquarters, Department of the Navy 1982) does not account for piles embedded in clay, it is recommended that Rowe's curves for both sands and clays be retained in CWALSHT.

References

Bowles, Joseph E. (1977). *Foundation analysis and design.* 2nd ed., McGraw-Hill, New York.

Dawkins, W. P. (1991). "User's guide: Computer program for design and analysis of sheet-pile walls by classical methods (CWALSHT) including Rowe's moment reduction," Instruction Report ITL-91-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg. MS.

__________. (1994). "User's guide: Computer program for 1D-SSI analysis of sheet-pile walls (CWALSSI)," Instruction Report ITL-94-5, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Headquarters, Department of the Army. (1994). "Design of sheet-pile walls," Engineer Manual 1110-2-2504, Washington, DC.

Headquarters, Department of the Navy. (1982). "Foundations and earth structures, Design Manual 7.2," NAVFAC 0525-LP-300-7070, Naval Facilities Engineering Command, Alexandria, VA.

Rowe, P. W. (1952). "Anchored sheet-pile walls." *Proceedings of Institution of Civil Engineers*. 1(1), 27-70.

__________. (1957). "Sheet Pile Walls in Clay." *Proceedings of Institution of Civil Engineers*. 7, 629-654.

United States Steel Corp. (1975). *Steel sheet piling design manual.* Pittsburgh, PA.

REPORT DOCUMENTATION PAGE					*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
September 2001

2. REPORT TYPE
Final Report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Investigation of Wall Friction, Surcharge Loads, and Moment Reduction Curves for Anchored Sheet-Pile Walls

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
William P. Dawkins

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

5818 Benning Drive
Houston, TX 77096

8. PERFORMING ORGANIZATION REPORT NUMBER

ERDC/ITL TR-01-4

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Corps of Engineers
Washington, DC 20314-1000;

U.S. Army Engineer Research and Development Center
Information Technology Laboratory
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report presents the results of three separate investigations pertaining to anchored sheet-pile walls. The effect of wall friction on bending moments computed using classical design procedures and one-dimensional soil-structure interaction is examined. Also comparisons are made between different methods of computing soil pressures which incorporate the effects of surcharge loads. Finally, moment reduction curves from several different sources are compared.

15. SUBJECT TERMS

Anchored	Sheet-pile wall	Surcharge
Moment reduction	Soil pressure	Wall Friction

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED		58	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

REPORTS PUBLISHED UNDER THE COMPUTER-AIDED STRUCTURAL ENGINEERING (CASE) PROJECT

	Title	Date
Technical Report K-78-1	List of Computer Programs for Computer-Aided Structural Engineering	Feb 1978
Instruction Report 0-79-2	User's Guide: Computer Program with Interactive Graphics for Analysis of Plane Frame Structures (CFRAME)	Mar 1979
Technical Report K-80-1	Survey of Bridge-Oriented Design Software	Jan 1980
Technical Report K-80-2	Evaluation of Computer Programs for the Design/Analysis of Highway and Railway Bridges	Jan 1980
Instruction Report K-80-1	User's Guide: Computer Program for Design/Review of Curvi-linear Conduits/Culveris (CURCON)	Feb 1980
Instruction Report K-80-3	A Three-Dimensional Finite Element Data Edit Program	Mar 1980
Instruction Report K-80-4	A Three-Dimensional Stability Analysis/Design Program (3DSAD)	
	Report 1: General Geometry Module	Jun 1980
	Report 3: General Analysis Module (CGAM)	Jun 1982
	Report 4: Special-Purpose Modules for Dams (CDAMS)	Aug 1983
Instruction Report K-80-6	Basic User's Guide: Computer Program for Design and Analysis of Inverted-T Retaining Walls and Floodwalls (TWDA)	Dec 1980
Instruction Report K-80-7	User's Reference Manual: Computer Program for Design and Analysis of Inverted-T Retaining Walls and Floodwalls (TWDA)	Dec 1980
Technical Report K-80-4	Documentation of Finite Element Analyses	
	Report 1: Longview Outlet Works Conduit	Dec 1980
	Report 2: Anchored Wall Monolith, Bay Springs Lock	Dec 1980
Technical Report K-80-5	Basic Pile Group Behavior	Dec 1980
Instruction Report K-81-2	User's Guide: Computer Program for Design and Analysis of Sheet Pile Walls by Classical Methods (CSHTWAL)	
	Report 1: Computational Processes	Feb 1981
	Report 2: Interactive Graphics Options	Mar 1981
Instruction Report K-81-3	Validation Report: Computer Program for Design and Analysis of Inverted-T Retaining Walls and Floodwalls (TWDA)	Feb 1981
Instruction Report K-81-4	User's Guide: Computer Program for Design and Analysis of Cast-in-Place Tunnel Linings (NEWTUN)	Mar 1981
Instruction Report K-81-6	User's Guide: Computer Program for Optimum Nonlinear Dynamic Design of Reinforced Concrete Slabs Under Blast Loading (CBARCS)	Mar 1981
Instruction Report K-81-7	User's Guide: Computer Program for Design or Investigation of Orthogonal Culverts (CORTCUL)	Mar 1981
Instruction Report K-81-9	User's Guide: Computer Program for Three-Dimensional Analysis of Building Systems (CTABS80)	Aug 1981
Technical Report K-81-2	Theoretical Basis for CTABS80: A Computer Program for Three-Dimensional Analysis of Building Systems	Sep 1981

(Continued)

REPORTS PUBLISHED UNDER THE COMPUTER-AIDED STRUCTURAL ENGINEERING (CASE) PROJECT

	Title	Date
Instruction Report K-82-6	User's Guide: Computer Program for Analysis of Beam-Column Structures with Nonlinear Supports (CBEAMC)	Jun 1982
Instruction Report K-82-7	User's Guide: Computer Program for Bearing Capacity Analysis of Shallow Foundations (CBEAR)	Jun 1982
Instruction Report K-83-1	User's Guide: Computer Program with Interactive Graphics for Analysis of Plane Frame Structures (CFRAME)	Jan 1983
Instruction Report K-83-2	User's Guide: Computer Program for Generation of Engineering Geometry (SKETCH)	Jun 1983
Instruction Report K-83-5	User's Guide: Computer Program to Calculate Shear, Moment, and Thrust (CSMT) from Stress Results of a Two-Dimensional Finite Element Analysis	Jul 1983
Technical Report K-83-1	Basic Pile Group Behavior	Sep 1983
Technical Report K-83-3	Reference Manual: Computer Graphics Program for Generation of Engineering Geometry (SKETCH)	Sep 1983
Technical Report K-83-4	Case Study of Six Major General-Purpose Finite Element Programs	Oct 1983
Instruction Report K-84-2	User's Guide: Computer Program for Optimum Dynamic Design of Nonlinear Metal Plates Under Blast Loading (CSDOOR)	Jan 1984
Instruction Report K-84-7	User's Guide: Computer Program for Determining Induced Stresses and Consolidation Settlements (CSETT)	Aug 1984
Instruction Report K-84-8	Seepage Analysis of Confined Flow Problems by the Method of Fragments (CFRAG)	Sep 1984
Instruction Report K-84-11	User's Guide for Computer Program CGFAG, Concrete General Flexure Analysis with Graphics	Sep 1984
Technical Report K-84-3	Computer-Aided Drafting and Design for Corps Structural Engineers	Oct 1984
Technical Report ATC-86-5	Decision Logic Table Formulation of ACI 318-77, Building Code Requirements for Reinforced Concrete for Automated Constraint Processing, Volumes I and 11	Jun 1986
Technical Report ITL-87-2	A Case Committee Study of Finite Element Analysis of Concrete Flat Slabs	Jan 1987
Instruction Report ITL-87-2 (Revised)	User's Guide for Concrete Strength Investigation and Design (CASTR) in Accordance with ACI 318-89	Mar 1992
Instruction Report ITL-87-1	User's Guide: Computer Program for Two-Dimensional Analysis of U-Frame Structures (CUFRAM)	Apr 1987
Instruction Report ITL-87-2	User's Guide: For Concrete Strength Investigation and Design (CASTR) in Accordance with ACI 318-83	May 1987
Technical Report ITL-87-6	Finite-Element Method Package for Solving Steady-State Seepage Problems	May 1987

(Continued)

REPORTS PUBLISHED UNDER THE COMPUTER-AIDED STRUCTURAL ENGINEERING (CASE) PROJECT

	Title	Date
Instruction Report ITL-87-3	User's Guide: A Three-Dimensional Stability Analysis/Design Program (3DSAD) Module	Jun 1987
	Report 1: Revision 1: General Geometry	Jun 1987
	Report 2: General Loads Module	Sep 1989
	Report 6: Free-Body Module	Sep 1989
Instruction Report ITL-87-4	User's Guide: 2-D Frame Analysis Link Program (LINK2D)	Jun 1987
Technical Report ITL-87-4	Finite Element Studies of a Horizontally Framed Miter Gate	Aug 1987
	Report 1: Initial and Refined Finite Element Models (Phases A, B, and C), Volumes I and 11	
	Report 2: Simplified Frame Model (Phase D)	
	Report 3: Alternate Configuration Miter Gate Finite Element Studies-Open Section	
	Report 4: Alternate Configuration Miter Gate Finite Element Studies-Closed Sections	
	Report 5: Alternate Configuration Miter Gate Finite Element Studies-Additional Closed Sections	
	Report 6: Elastic Buckling of Girders in Horizontally Framed Miter Gates	
	Report 7: Application and Summary	
Instruction Report GL-87-1	User's Guide: UTEXAS2 Slope-Stability Package; Volume 1, User's Manual	Aug 1987
Instruction Report ITL-87-5	Sliding Stability of Concrete Structures (CSLIDE)	Oct 1987
Instruction Report ITL-87-6	Criteria Specifications for and Validation of a Computer Program for the Design or Investigation of Horizontally Framed Miter Gates (CMITER)	Dec 1987
Technical Report ITL-87-8	Procedure for Static Analysis of Gravity Dams Using the Finite Element Method - Phase Ia	Jan 1988
Instruction Report ITL-88-1	User's Guide: Computer Program for Analysis of Planar Grid Structures (CGRID)	Feb 1988
Technical Report ITL-88-1	Development of Design Formulas for Ribbed Mat Foundations on Expansive Soils	Apr 1988
Technical Report ITL-88-2	User's Guide: Pile Group Graphics Display (CPGG) Postprocessor to CPGA Program	Apr 1988
Instruction Report ITL-88-2	User's Guide for Design and Investigation of Horizontally Framed Miter Gates (CMITER)	Jun 1988
Instruction Report ITL-88-4	User's Guide for Revised Computer Program to Calculate Shear, Moment, and Thrust (CSMT)	Sep 1988
Instruction Report GL-87-1	User's Guide: UTEXAS2 Slope-Stability Package; Volume 11, Theory	Feb 1989
Technical Report ITL-89-3	User's Guide: Pile Group Analysis (CPGA) Computer Group	Jul 1989

(Continued)

REPORTS PUBLISHED UNDER THE COMPUTER-AIDED STRUCTURAL ENGINEERING (CASE) PROJECT

	Title	Date
Technical Report ITL-89-4	CBASIN-Structural Design of Saint Anthony Falls Stilling Basins According to Corps of Engineers Criteria for Hydraulic Structures; Computer Program X0098	Aug 1989
Technical Report ITL-89-5	CCHAN-Structural Design of Rectangular Channels According to Corps of Engineers Criteria for Hydraulic Structures; Computer Program X0097	Aug 1989
Technical Report ITL-89-6	The Response-Spectrum Dynamic Analysis of Gravity Dams Using the Finite Element Method; Phase 11	Aug 1989
Contract Report ITL-89-1	State of the Art on Expert Systems Applications in Design, Construction, and Maintenance of Structures	Sep 1989
Instruction Report ITL-90-1	User's Guide: Computer Program for Design and Analysis of Sheet Pile Walls by Classical Methods (CWALSHT)	Feb 1990
Instruction Report ITL-90-2	User's Guide: Pile Group-Concrete Pile Analysis Program (CPGC) Preprocessor to CPGA Program	Jun 1990
Instruction Report ITL-90-3	Investigation and Design of U-Frame Structures Using Program CUFRBC	
	Volume A: Program Criteria and Documentation	May 1990
	Volume B: User's Guide for Basins	May 1990
	Volume C: User's Guide for Channels	May 1990
Instruction Report ITL-90-6	User's Guide: Computer Program for Two-Dimensional Analysis of U-Frame or W-Frame Structures (CWFRAM)	Sep 1990
Technical Report ITL-91-3	Application of Finite Element, Grid Generation, and Scientific Visualization Techniques to 2-D and 3-D Seepage and Groundwater Modeling	Sep 1990
Instruction Report ITL-91-1	User's Guide: Computer Program for Design and Analysis of Sheet-Pile Walls by Classical Methods (CWALSHT) Including Rowe's Moment Reduction	Oct 1991
Technical Report ITL-92-2	Finite Element Modeling of Welded Thick Plates for Bonneville Navigation Lock	May 1992
Technical Report ITL-92-4	Introduction to the Computation of Response Spectrum for Earthquake Loading	Jun 1992
Instruction Report ITL-92-3	Concept Design Example, Computer-Aided Structural Modeling (CASM)	
	Report 1: Scheme A	Jun 1992
	Report 2: Scheme B	Jun 1992
	Report 3: Scheme C	Jun 1992
Instruction Report ITL-92-4	User's Guide: Computer-Aided Structural Modeling (CASM) – Version 3.00	Apr 1992
Instruction Report ITL-92-5	Tutorial Guide: Computer-Aided Structural Modeling (CASM) - Version 3.00	Apr 1992

(Continued)

REPORTS PUBLISHED UNDER THE COMPUTER-AIDED STRUCTURAL ENGINEERING (CASE) PROJECT

	Title	Date
Contract Report ITL-92-1	Optimization of Steel Pile Foundations Using Optimality Criteria	Jun 1992
Technical Report ITL-92-7	Refined Stress Analysis of Melvin Price Locks and Dam	Sep 1992
Contract Report ITL-92-2	Knowledge-Based Expert System for Selection and Design of Retaining Structures	Sep 1992
Contract Report ITL-92-3	Evaluation of Thermal and Incremental Construction Effects for Monoliths AL-3 and AL-5 of the Melvin Price Locks and Dam	Sep 1992
Instruction Report GL-87-1	User's Guide: UTEXAS3 Slope-Stability Package; Volume IV, User's Manual	Nov 1992
Technical Report ITL-92-11	The Seismic Design of Waterfront Retaining Structures	Nov 1992
Technical Report ITL-92-12	Computer-Aided, Field-Verified Structural Evaluation	
	Report 1: Development of Computer Modeling Techniques for Miter Lock Gates	Nov 1992
	Report 2: Field Test and Analysis Correlation at John Hollis Bankhead Lock and Dam	Dec 1992
	Report 3: Field Test and Analysis Correlation of a Vertically Framed Miter Gate at Emsworth Lock and Dam	Dec 1993
Instruction Report GL-87-1	Users Guide: UTEXAS3 Slope-Stability Package; Volume III, Example Problems	Dec 1992
Technical Report ITL-93-1	Theoretical Manual for Analysis of Arch Dams	Jul 1993
Technical Report ITL-93-2	Steel Structures for Civil Works, General Considerations for Design and Rehabilitation	Aug 1993
Technical Report ITL-93-3	Soil-Structure Interaction Study of Red River Lock and Dam No. 1 Subjected to Sediment Loading	Sep 1993
Instruction Report ITL-93-3	User's Manual-ADAP, Graphics-Based Dam Analysis Program	Aug 1993
Instruction Report ITL-93-4	Load and Resistance Factor Design for Steel Miter Gates	Oct 1993
Technical Report ITL-94-2	User's Guide for the Incremental Construction, Soil-Structure Interaction Program SOILSTRUCT with Far-Field Boundary Elements	Mar 1994
Instruction Report ITL-94-1	Tutorial Guide: Computer-Aided Structural Modeling (CASM); Version 5.00	Apr 1994
Instruction Report ITL-94-2	User's Guide: Computer-Aided Structural Modeling (CASM); Version 5.00	Apr 1994
Technical Report ITL-94-4	Dynamics of Intake Towers and Other MDOF Structures Under Earthquake Loads: A Computer-Aided Approach	Jul 1994
Technical Report ITL-94-5	Procedure for Static Analysis of Gravity Dams Including Foundation Effects Using the Finite Element Method - Phase 1 B	Jul 1994
Instruction Report ITL-94-5	User's Guide: Computer Program for Winkler Soil-Structure Interaction Analysis of Sheet-Pile Walls (CWALSSI)	Nov 1994

(Continued)

REPORTS PUBLISHED UNDER THE COMPUTER-AIDED STRUCTURAL ENGINEERING (CASE) PROJECT

	Title	Date
Instruction Report ITL-94-6	User's Guide: Computer Program for Analysis of Beam-Column Structures with Nonlinear Supports (CBEAMC)	Nov 1994
Instruction Report ITL-94-7	User's Guide to CTWALL - A Microcomputer Program for the Analysis of Retaining and Flood Walls	Dec 1994
Contract Report ITL-95-1	Comparison of Barge Impact Experimental and Finite Element Results for the Lower Miter Gate of Lock and Dam 26	Jun 1995
Technical Report ITL-95-5	Soil-Structure Interaction Parameters for Structured/Cemented Silts	Aug 1995
Instruction Report ITL-95-1	User's Guide: Computer Program for the Design and Investigation of Horizontally Framed Miter Gates Using the Load and Resistance Factor Criteria (CMITER-LRFD)	Aug 1995
Technical Report ITL-95-8	Constitutive Modeling of Concrete for Massive Concrete Structures, A Simplified Overview	Sep 1995
Instruction Report ITL-96-1	Use's Guide: Computer Program for Two-Dimensional Dynamic Analysis of U-Frame or W-Frame Structures (CDWFRM)	Jun 1996
Instruction Report ITL-96-2	Computer-Aided Structural Modeling (CASM), Version 6.00 Report 1: Tutorial Guide Report 2: User's Guide Report 3: Scheme A Report 4: Scheme B Report 5: Scheme C	Jun 1996
Technical Report ITL-96-8	Hyperbolic Stress-Strain Parameters for Structured/Cemented Silts	Aug 1996
Instruction Report ITL-96-3	User's Guide: Computer Program for the Design and Investigation of Horizontally Framed Miter Gates Using the Load and Resistance Factor Criteria (CMITERW-LRFD) Windows Version	Sep 1996
Instruction Report ITL-97-1	User's Guide: Computer Aided Inspection Forms for Hydraulic Steel Structures (CAIF-HSS), Windows Version	Sep 1996
Instruction Report ITL-97-2	User's Guide: Arch Dam Stress Analysis System (ADSAS)	Aug 1996
Instruction Report ITL-98-1	User's Guide for the Three-Dimensional Stability Analysis/Design (3DSAD) Program	Sep 1998
Technical Report ITL-98-4	Investigation of At-Rest Soil Pressures due to Irregular Sloping Soil Surfaces and CSOILP User's Guide	Sep 1998
Technical Report ITL-98-5	The Shear Ring Method and the Program Ring Wall	Sep 1998
Technical Report ITL-98-6	Reliability and Stability Assessment of Concrete Gravity Structures (RCSLIDE): Theoretical Manual	Dec 1998

(Continued)

REPORTS PUBLISHED UNDER THE COMPUTER-AIDED STRUCTURAL ENGINEERING (CASE) PROJECT

(Concluded)

	Title	Page
Technical Report ITL-99-1	Development of an Improved Numerical Model for Concrete-to-Soil Interfaces in Soil-Structure Interaction Analyses	
	Report 1: Preliminary Study	Jan 1999
	Report 2: Final Study	Aug 2000
Technical Report ITL-99-5	River Replacement Analysis	Dec 1999
ERDC/ITL TR-00-1	Evaluation and Comparison of Stability Analysis and Uplift Criteria for Concrete Gravity Dams by Three Federal Agencies	Jan 2000
ERDC/ITL TR-00-2	Reliability and Stability Assessment of Concrete Gravity Structures (RCSLIDE): User's Guide	Jul 2000
ERDC/ITL TR-00-5	Theoretical Manual for Pile Foundations	Nov 2000
ERDC/ITL TR-01-2	SOILSTRUCT-ALPHA for Personal Computers Report 1: Visual Modeler	Dec 2001
ERDC/ITL TR-01-3	Finite Element Modeling of Cooling Coil Effects in Mass Concrete Systems	Aug 2001
ERDC/ITL TR-01-4	Investigation of Wall Friction, Surcharge Loads, and Moment Reduction Curves for Anchored Sheet-Pile Walls	Sep 2001